University of Canterbury

Fire Safety System Effectiveness for a Risk-Informed Design Tool

by

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Quotes:

”There is nothing more difficult to carry out, nor more dangerous to handle, than to initiate a new order of things. For the reformer (innovator) has enemies in all those who profit by the old order, and only lukewarm defenders in all those who would profit by the new.”

Machiavelli

”...a choice made with uncertainty-colored glasses on rather than blinders is a superior choice, one that can engender justifiable rather than false confidence in one’s actions.”

Adam M. Finkel

”When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science.”

Lord Kelvin

”For every complex problem, there is a solution that is simple, neat, and wrong.”

Henry L. Mencken

”All models are wrong, but some are useful.”

George E. P. Box

Abstract

The purpose of this research is to identify how uncertainty in fire safety system effectiveness should be considered in a new risk-informed design fire tool, B-RISK. Specific objectives were to collect the available data on fire safety system effectiveness from the literature, investigate methods to improve fire safety system effectiveness data collection, develop the risk-informed design fire tool to propagate the uncertainties, and recommend methods to rank the sources of uncertainty for fire safety system effectiveness for appropriate model selection. The scope of the research is limited to the effects of systems on fire development and smoke spread and does not include the effects of the fire on systems (such as loss of structural integrity) or interactions with occupants. Sprinkler effectiveness data from recent New Zealand Fire Service data is included with a discussion of the uncertainty in this type of data and recommendations for improving data collection. The ability of the model to predict multiple sprinkler activations is developed in conjunction with a hydraulic submodel in B-RISK to include water supply pressure effects on sprinkler effectiveness. A new method of collecting reliability data on passive fire protection elements such as doors was developed. Data collected on the probability for doors in shared means of escape to be open and the time doors are open during occupant evacuation using this method is presented. Available data on smoke management system effectiveness is listed, along with a discussion of why there is more uncertainty associated with these systems compared with sprinkler systems. The capabilities of B-RISK for considering fire safety system effectiveness are demonstrated using Australasian case studies.

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Finally Jenna, for all the support and company on our adventures in New Zealand.

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α . . . . t^2 fire growth rate parameter [kW/s^2]

C . . . . Conduction factor [$(m/s)^{1/2}$]

C . . . . Hazen Williams pipe roughness constant [-]

C_{soot} . . . . Soot concentration [kg/kg]

χ_{rad} . . . . Radiant loss fraction [-]

d . . . . Mean bore diameter [m]

FED_g . . . . Fractional effective dose of toxic gases [-]

FED_{th} . . . . Fractional effective dose of thermal radiation [-]

g . . . . Gravitational acceleration [9.81 m/s^2]

h . . . . Height or head [m]

h_c . . . . Heat of combustion [MJ/kg]

HRR . . . . Heat release rate [kW]

$HRRPUA$ . . . . Heat release rate per unit area [kW/m^2]

K .... Sprinkler discharge coefficient [$\frac{L/min}{\sqrt{kPa}}$]

λ .... Exponential decay parameter [-]

$\mathbf{m}$ .... Magnetic field vector [gauss]

$\mathbf{m_1}$ .... Magnetic field vector at door position 1 [gauss]

$\mathbf{m_2}$ .... Magnetic field vector at door position 2 [gauss]

μ .... Mean [-]

OD .... Optical density [OD/m]

$P()$ .... Probability (scale of 0 to 1)

P .... Pressure [kPa]

ϕ .... Angle of magnetic field to vertical axis [^{o}]

Q .... Flow rate [L/min]

RTI .... Response time index (m s$^{1/2}$)

ρ .... Density [kg/m^3]

σ .... Standard deviation [-]

T_{amb} .... Ambient temperature [^{o}C]

T_d .... Detector temperature [^{o}C]

T_{gas} .... Gas temperature [^{o}C]

T_{act} .... Detector activation temperature [^{o}C]

t .... Time [s]

t_{act} .... Detector activation time [s]

θ .... Door open angle [^{o}]

u .... X-direction velocity [m/s]

w'' .... Sprinkler spray density [mm/min]

ASET .... Available safe egress time

BCA .... Building Consent Authority

BCA .... Building Code of Australia

BIA .... Building Industry Authority

BIC .... Building Industry Commission

BRANZ .... Building Research Association of New Zealand

C/AS1-C/AS6 .... New Zealand acceptable solutions for fire safety in buildings

CFAST .... Consolidated model of fire growth and smoke transport

C/VM2 .... New Zealand verification method for fire safety in buildings

DBH .... New Zealand Department of Building and Housing

DTS .... Deemed to satisfy

EHH .... Extra high hazard

ELH .... Extra light hazard

FDS .... Fire Dynamics Simulator

FIP .... Fire indicating panel

FLED .... Fire load energy density

FM .... Factory Mutual

FPANZ .... Fire Protection Association of New Zealand

FRST .... Foundation for Research, Science and Technology

FTP .... Flux time product

GDP .... Gross domestic product

GER .... Global equivalence ratio

HVAC .... Heating, ventilation, and air conditioning

I2C .... Inter-integrated circuit

IFEG .... International Fire Engineering Guidelines

IQP	Independently qualified person
ISO	International Organization for Standardization
MSI	Ministry of Science and Innovation
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NZBC	New Zealand Building Code
NZD	New Zealand dollars
NZFS	New Zealand Fire Service
NZS	New Zealand Standard
OH	Ordinary hazard
QRA	Quantitative risk assessment
RF	Radio frequency
ROO	Room of origin
RSET	Required safe egress time
SME	Single means of escape
SSC	Sprinkler System Certifier
TA	Territorial authority
TALL	Total acceptable loss of life
UL	Underwriters' Laboratories
WS	Water supply
XML	Extensible markup language

CHAPTER 1

INTRODUCTION

1.1 Overview

AN architect wants to eliminate an exit stairway to conserve valuable space in a high density area high-rise building. A building owner thinks that putting in fire-rated wall assemblies will be more cost-effective than installing a sprinkler system. A historical organisation wants to know what the best options are to improve the fire safety of their buildings and contained artefacts within a limited budget but limiting the impacts on the authenticity of their facilities. Traditional prescriptive fire safety regulations would not allow such flexibility in design, and while modern performance-based fire safety regulations potentially may, it is currently difficult to quantify the potential effects of these and other decisions on building fire safety.

Under traditional prescriptive fire safety regulations the building design is essentially specified by the regulations and there is generally little room for flexibility or trade-offs to make a building more fit-for-purpose. The performance-based paradigm shifts the regulatory requirements from specific building design itself to the societal objectives that the building design is intended to achieve. Any building design is allowed so long as it meets this performance criteria. In the case of fire, performance-based objectives may be the life safety of occupants or rescuers, the protection of property, or the protection of the environment. However, it is difficult to accurately quantify the effects of fire safety systems on the level of risk, so it becomes difficult to determine if trade-offs among systems achieve the required level of safety [1]. Can a means of escape be removed if a smoke management system is installed? Can the fire resistance rating of fire compartments be reduced if a sprinkler system is installed? In a performance-based environment, the building regulator as society's representative has a difficult task in determining what is acceptable, particularly so because it is difficult to quantify the effectiveness of fire safety systems over the lifetime of buildings.

In the wider societal context, knowledge of system effectiveness is also necessary to evaluate where scarce economic resources should be spent. Are air bags more effective at saving lives than sprinkler systems per dollar of cost to society? Would more lives be saved per dollar by installing automatic defibrillators in buildings rather than smoke management systems?

The need to research the quantitative effect of fire safety systems on building fire safety has been discussed in the literature. In the move towards risk- and performance-based fire safety design Notarianni and Fischbeck[2] identified *"seven major barriers to determining and documenting achievement of agreed upon levels of fire safety"*, one of which was that *"no standardized methods exist to incorporate reliability of systems."* At an October 2006 meeting in Wellington, New Zealand, the International Forum of Fire Research Directors which includes members from the Building Research Association of New Zealand (BRANZ), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the National Institute of Standards and Technology (NIST), FM Global, the National Research Council of Canada (NRCC), and the Society of Fire Protection Engineers (SFPE) among others, listed:

- *"to improve our ability to predict the impact of active fire protection systems on the fire growth and fate of combustion products; and*
- *to estimate the various contributions to uncertainty and to incorporate them into hazard and risk analyses"*

as two of their top five research priorities[3] for developing the next generation of performance-based fire safety design tools[4]. Beyler[5] stated that *"the reliability of fire suppression systems remain[s] a subject of great uncertainty due to our unwillingness or inability to assess reliability from historical data."* A New Zealand example where the inability to quantify fire safety system effectiveness was a substantial barrier to evaluating alternative fire designs occured in the single means of escape determinations in 2005-2006, which will be discussed in detail later in Chapter11.

There is no question that there is uncertainty in our current ability to quantify the effectiveness of fire safety systems. It is impossible to expect that we will be able to predict the fire safety systems' effectiveness over the lifetime of a building with certainty, because building contents, human behaviour, and occupancy will change as the building use changes, technology advances, and society evolves. This research does not attempt to remove all uncertainty in this matter, but it does attempt to define a process to consider the uncertainty in the effectiveness of fire safety systems for the purpose of performance-based building fire safety design. Bernstein[6] discusses the three main dangers of quantifying risk in general: *"exposure to discontinuities, the arrogance of quantifying the unquantifiable, and the threat of increasing risk rather than managing it"*. These potential pitfalls should be remembered when making risk-informed fire safety decisions.

This research study has a number of objectives related to uncertainty in estimating fire safety system effectiveness. The first is to discuss the historical context of the fire problem and building fire regulations, and how it has influenced the current fire safety environment in New Zealand and led to the need for this research. Second, to explore the available data on overall system reliability and efficacy, characterising the uncertainty and observing where technological progress may allow for improvements in data collection to provide better fire safety system effectiveness information to inform fire safety design. The third is to develop the ability of a new probabilistic-deterministic model to include the effects and uncertainties of fire safety systems. A probabilistic-deterministic model allows probability distributions to describe the uncertainty in the input parameters used in a deterministic model, providing an estimated range of output possibilities given the uncertainty in the inputs. The fourth is a discussion of the relative contribution of different sources of uncertainties for typical design scenarios and the adequacy of the model to provide a "consistent level of crudeness"[7] with the variability in the scenario inputs. The fifth is to demonstrate how the new model might be applied for fire safety design. Due to the diversity of topics covered in this document there is no explicit literature review. Instead, literature review is embedded in appropriate sections as required for individual systems or other topics such as fire risk models.

The scope of this research is limited to the effect of fire safety systems on the early development stages of the fire. Thus the effects of fire on passive system elements once it reaches a fully developed state are not included. Occupant response during a fire is not explicitly considered, although the behaviour of people will affect the performance of fire safety systems and these effects are implicitly included in the data. Examples are occupants wedging open a fire door or shutting off a sprinkler valve.

The first chapter discusses the background and development of building regulation in western countries, focusing on New Zealand in particular, and the reasons why this research is important for future fire safety in New Zealand. Recent cost estimates for fire risk in New Zealand buildings are included. The current practice for considering fire safety system effectiveness in New Zealand for performance-based fire safety building design is discussed. Definitions of terms describing system effectiveness and uncertainty classifications are introduced.

Chapter 2 covers existing fire risk computer models that have been developed around the world. The structure of the new risk informed fire design tool B-RISK is described. As this work was completed over a period of three years during which time B-RISK was evolving through versions, various versions were used for different sections of this thesis. The version used for each section is listed in the chapters and in this overview.

Chapter 3 explores existing studies and data sources which provide information on sprinkler system effectiveness. Some of the results of Chapter 4 are included for comparison. This chapter is based on a paper that was submitted to the journal *Fire Science Reviews*.

Chapter 4 examines recent New Zealand Fire Service data on fires in sprinklered buildings. This chapter is based on a paper that was published in the journal *Fire Technology*.

Chapter 5 analyses the uncertainty in the ability to predict the initial time of sprinkler activation. A comparison between model uncertainties and natural variability is included for two scenarios. The suitability of using a two-zone model as the deterministic engine for the model is discussed. This chapter is based on a paper that was presented at the 10th International Symposium on Fire Safety Science held at the University of Maryland in June 2011. A preliminary version of B-RISK that was essentially a modified version of BRANZFire was used as the deterministic model with the commercial packages @Risk and Excel used for the probabilistic inputs and for collating the outputs for this chapter.

A new method of modifying sprinklers to measure their thermal response is described in Chapter 6. The modified sprinkler response is compared to actual sprinklers in wind tunnel tests and a fire compartment test and thermal response models, including B-RISK. The thermal detector response models in B-RISK versions 23 and 48 are compared to BRANZFire 2011.2 in this chapter.

The methods used in the new model to estimate the effects of sprinklers on fire development are the topic of Chapter 7. A comparison of the model's capability to estimate the activation of multiple sprinklers is included that is based on a paper that was presented at the SFPE 9th International Conference on Performance-Based Codes and Fire Safety Design Methods held in Hong Kong in June 2012. B-RISK version 17 was used for this portion of the chapter. An illustrative example of the effects of changing water supply on the number of sprinklers activated in B-RISK is then given, for which B-RISK version 28 was used.

Existing data on the effectiveness of passive building elements is described in Chapter 8.

Chapter 9 describes the development of a novel method of collecting door effectiveness data. Data from the new method is presented.

The uncertainties regarding smoke management system effectiveness are covered in Chapter 10. Smoke detection uncertainty is included because smoke detectors are used as a means of activating a smoke management system.

Four relevant case studies are introduced in Chapter 11. Two examples of risk-informed fire safety design in New Zealand are presented; the analysis of the Type 5 alarm introduction to the fire safety acceptable solution C/AS1 completed by Enright in 2003[8], and the set of determinations regarding single means of escape alternative designs for highrise residential buildings in Auckland in 2005 and 2006. A third regional example of risk-informed fire safety design in a commercial office building in Australia, the 140 William Street building in Melbourne, is also included. The areas of focus for this research which are driven by the outcomes of these case studies are introduced. A fourth case study on a fire that occurred in a seniors' assisted living complex in Alberta, Canada is included to demonstrate the influence of fire safety systems on fire development and as an example of building regulation changes due to fire safety system effectiveness.

A discussion of how the model would be used for risk-informed fire safety engineering is included in Chapter 12. Two of the buildings from the case studies from Chapter 11 are used in this chapter. B-RISK version 48 was used for this chapter.

Chapter 13 provides a set of conclusions and recommendations for future work.

1.2 Cost of fire in New Zealand

According to the World Fire Statistics Centre[9], the direct cost of fire losses in New Zealand ranged from 165 million NZD to 180 million NZD from 2005 to 2007, which was approximately 0.11% of gross domestic product (GDP). Indirect costs were estimated at 0.007% of GDP in 2004. The cost of firefighting organisations, fire insurance administration, and fire protection to buildings was estimated at 0.16% GDP, 0.08% GDP, and 0.24% GDP, respectively. The cost of fire protecting buildings as a percentage of GDP in a number of countries can be seen in Figure 1.1, and the percentage of the fire losses as a percentage of the total amount spent on fire protection can be seen in Figure 1.2. While New Zealand was below average in fire protection spending for the countries considered, fire losses in New Zealand were low relative to the total amount of fire protection spending, indicating that New Zealand building practices may be more conservative than in other countries.

A study completed in 2005 by Business and Economic Research Limited for the NZFS estimated the total annual cost of the fire risk in New Zealand to be 1.02 billion NZD, or 0.79% of the national gross domestic product[10]. The components of the estimated annual cost of fire from the study can be seen in Figure 1.3. Of the total cost of fire, 285 million NZD or 28% was estimated to be spent on building fire protection features annually.

1.3 A synopsis of building regulations

The value of this research project is driven by the current and proposed future building regulation system in New Zealand. This section contains a description of the prescriptive- and performance-based approaches to building regulation and a brief overview of building regulation development with a focus on New Zealand.

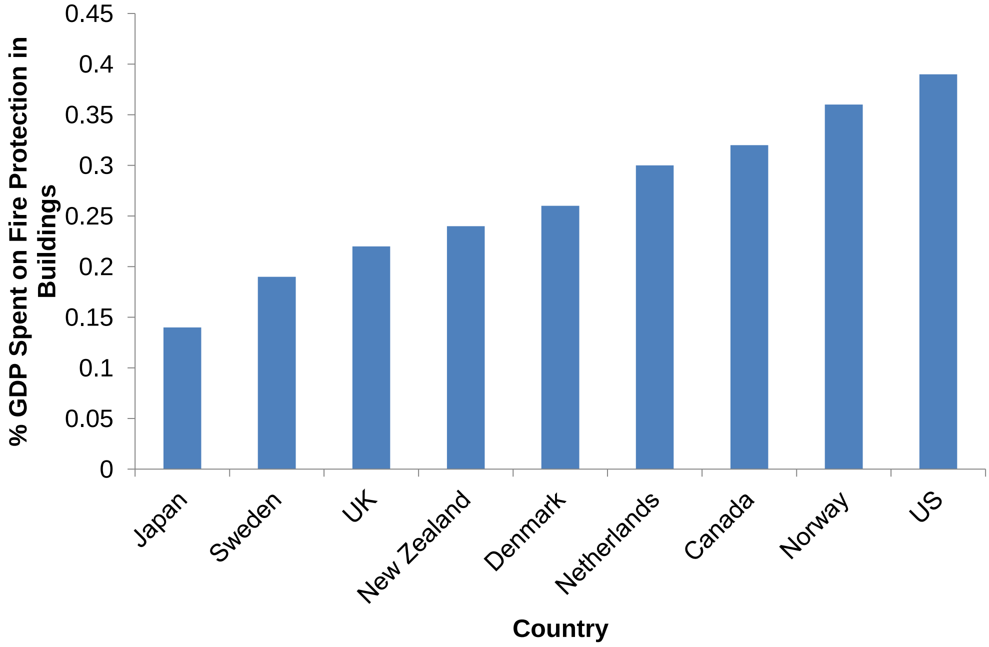

Figure 1.1: Cost of fire protection in buildings by country as a percentage of GDP[9].

1.3.1 Prescriptive-based vs. performance-based

Building regulations are generally described as being either prescriptive-based or performance-based. Prescriptive-based approaches provide specific criteria for building design and can be thought of as binary - either the design meets the criteria or it does not[11]. While prescriptive-based regulations are very specific on how buildings are to be built, they often do not discuss the rationale behind the requirements. The inflexibility and lack of information on the intent of prescriptive-based building regulations has been cited as creating barriers to international trade, restricting innovation in building design, reducing building cost-effectiveness, and even affecting the competitiveness of goods and services[12,13,14].

The concept of performance-based building regulation is to eliminate specific prescriptive criteria for the construction details of buildings, and to replace them with performance requirements that must be met to satisfy the regulations. Variations of performance-based regulation concepts have been adopted by many countries including New Zealand, Australia, Canada, and the UK[15]. This has not just

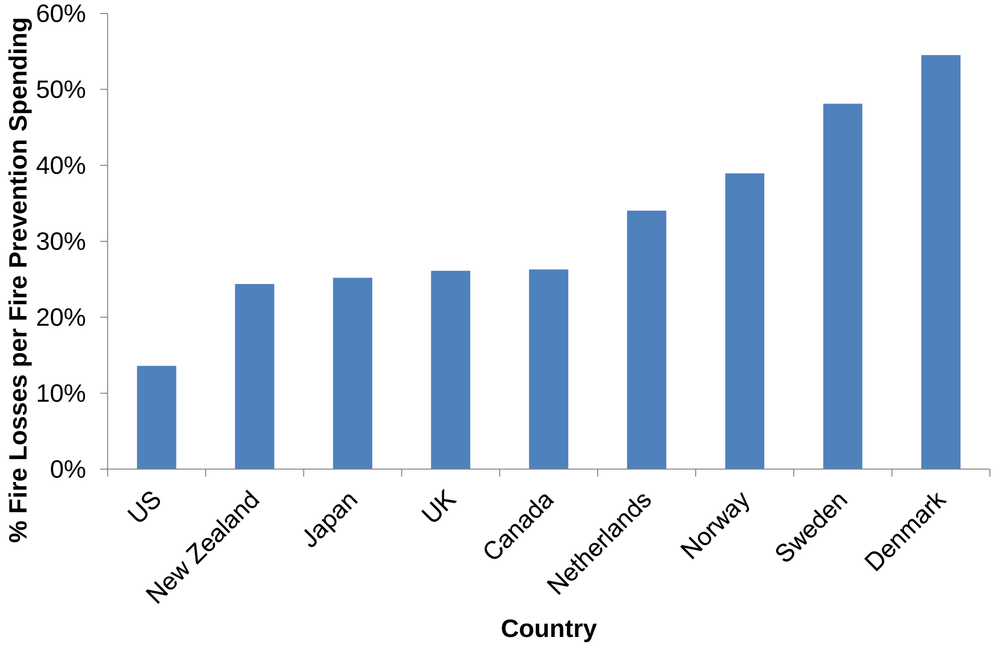

Figure 1.2: Fire losses as a percentage of fire prevention costs (including fire fighting organizations, fire insurance administration, and building fire protection feature cost[9].

been limited to building regulation, but other areas such as transport[16] and financial regulation (where the approach is known as principles-based regulation[17]). Meacham defines the requirements of performance-basis as follows: "In its most complete form, a performance-based approach includes acceptance (performance) criteria which can be quantified, measured, and/or calculated and verification methods which together serve as the metrics and methods for demonstrating compliance"[15].

1.3.2 History of fire safety regulations

The first known building code is generally attributed to Hammurabi, written in 229 BC and included in his code of laws. The first law pertaining to buildings reads "If a builder builds a house for someone, and does not construct it properly, and the house which he built falls in and kills its owner, then the builder shall be put to

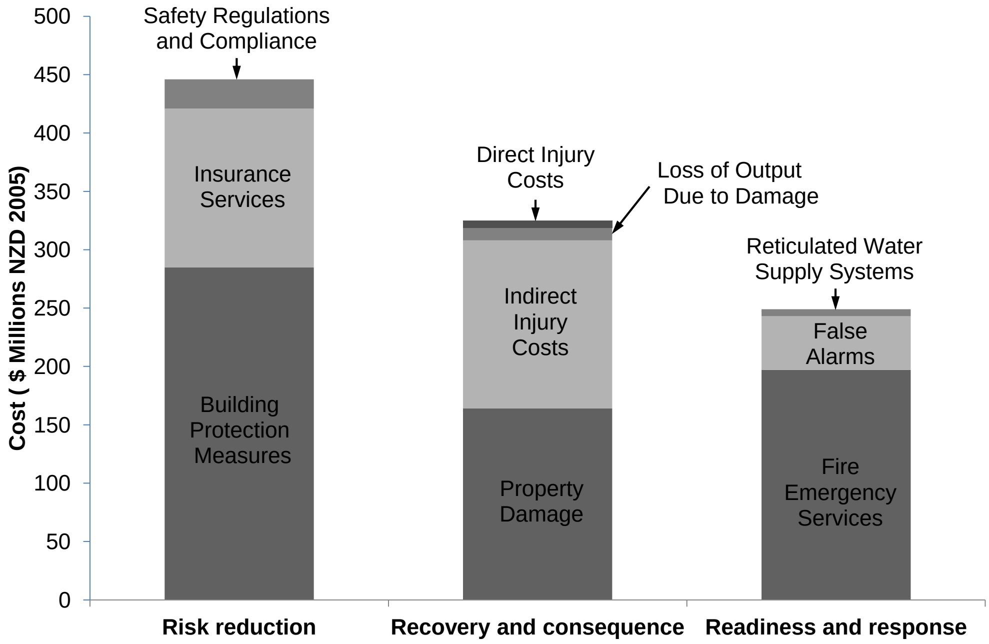

Figure 1.3: Annual total cost of fire in New Zealand in 2005[10].

death." This is an example of a performance-based building code, essentially stating that the house must only be designed to protect the owner's life from structural collapse, with no specification as to how the builder should achieve this requirement.

Many of the early prescriptive building fire safety regulations were driven by reactions to large loss fires, and were designed to prevent large-scale urban conflagrations. While the London fire of 1666, the Baltimore fire of 1904, and the Chicago fire of 1871 are often discussed in recent literature, a quick Google search for *great fire of [insert city name here]* reveals many other cities that suffered similar disasters (in no particular order):

- Great fire of Toronto, 1849, 1904
- Great fire of Boston, 1872
- Great Fire of New York, 1776, 1835
- Great fire of Rome AD, 64

- Great fire of Montreal, 1789
- Great fire of Christchurch, 1908
- Great fire of Seattle, 1889
- Great fire of Vancouver, 1886
- Great fire of Melbourne, 1897
- Great fire of Sydney, 1890
- Great fire of Atlanta, 1917
- Great fire of Baltimore, 1904
- Great fire of Calgary, 1886

to name a few, although the scope of the fire damage varies and the definition of a "great fire" is not always consistent. According to Tacitus, the Roman emperor Nero's reaction to the 64 AD Rome fire included restrictions on building materials such that they were impervious to fire[18]. The 1666 London fire and subsequent rebuilding provides a classical example of reactive prescriptive requirements after a large fire. Historical accounts of the fire[19] describe the city as having many timber-clad structures, with narrow streets and causeways between them. The narrow separation between buildings at street level was often diminished further as the upper stories often overhung the street. In 1667, an Act for rebuilding the city of London was passed, which included such prescriptive statements as requiring the exterior of all buildings in and about the city to be of brick or stone, or brick and stone[20].

Other fires where there was a large loss of life but less property loss also caused prescriptive requirements to come into force for the protection of life. For example, the Triangle Waist Company fire in 1911 New York led to the Factory Investigation Committee Report of 1912[21] which resulted in many changes including the adoption of exit signs. Building codes in most Western countries remained prescriptive documents until the concept of the performance-based approach became popular in the second half of the 20th century.

The origin of the modern performance-based approach is usually attributed to the Nordic countries where the mention of such approaches began in 1963, culminating in the Nordic Committee on Building Regulations Report 28, issued in

1976[22]. Canada experimented with a performance based section in the National Building Code of Canada 1965[23]. Section 9, Housing, included a single statement for fire protection, *"appropriate requirements for the protection of life in the event of fire and to restrict the spread of fire throughout the building or to other buildings should be in accordance with good practice[24]."* The United States began discussing "systematic approaches" to fire safety in 1971[25].

Meacham[15] provides an overview of the transition of building codes from prescription-based to performance-based in many countries worldwide, including Australia, Austria, Canada, China, Japan, England and Wales, Japan, the Netherlands, New Zealand, Norway, Scotland, Singapore, Spain, Sweden, and the United States of America. The following section discusses the history of building regulation in New Zealand.

1.3.3 A history of New Zealand building regulations

1.3.3.1 1886-1990

The history of building controls in New Zealand can be traced back to the 1886 Municipal Corporations Act which gave the power to make bylaws *"for any purpose in relation to... buildings ..."*[26] to local authorities, setting the stage for the local administration of building controls at the municipal level, which still partially remains at present. A timeline of significant events in New Zealand building regulation related to fire safety is shown in Figure 1.4.

The New Zealand Standards Institution (which later became the New Zealand Standards Institute and is now Standards New Zealand) was set up in 1932 as a result of the Napier earthquake of February 3, 1931 which resulted in 258 fatalities[27]. The standards organisation initiated a Building Code Committee in May 1934 and published model building bylaws from 1935 onwards[28]. Most municipal authorities recognized the model building bylaws from 1964 until the national building code was created in 1991, but by the late 1970s the bureaucracy had proliferated to the point where there were 60 Acts involved in building regulations[22], administered by 213 territorial authorities (TAs), comprised of city, town, and borough councils, along with 22 regional authorities, 19 United Councils and over 400 special purpose authorities. This TA structure had essentially remained unchanged since

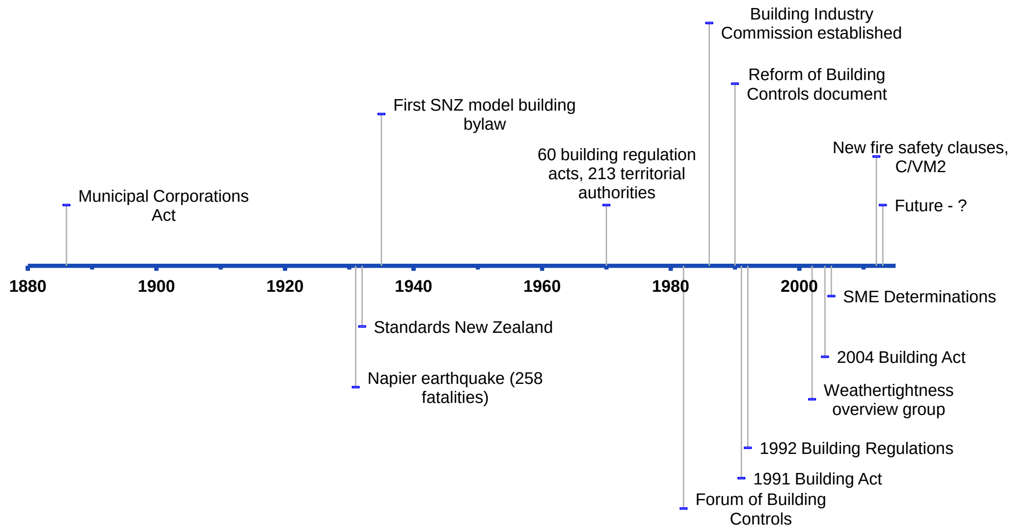

Figure 1.4: Timeline of events in New Zealand building regulation history.

1876[29]. Widespread concern was raised that overbearing and segmented building controls were substantially increasing building costs without corresponding benefits to the stakeholders. The need to reduce the proliferation of building controls and the resultant spending on administration was identified by many stakeholders at the Forum of Building Controls held in February, 1982 by the Department of Internal Affairs[30].

The concept of a performance-based national building code was discussed in New Zealand as early as the early 1980s by the Office of the Review of Planning and Building Controls[31]. The 5-level Nordic methodology previously established was recommended for use in New Zealand, and is described as follows:

1. (a) *the overall statement of the properties of a building that must be regarded as important from the point of view of society and individual members;*
   (b) *the main properties specified as the overall goal level classified in functional areas, and principles laid down for the realisation of the specified*

intentions;

(c) *operative requirements in order that principles laid down under [statutory requirements] within the various functional areas may be applied in the design and construction of buildings;*

2. *instructions or guidelines laid down for verification of compliance with the requirements;*
3. *supplement to the regulations with examples of acceptable solutions, deemed to satisfy the regulations*[31].

The Office of the Review of Planning and Building Controls also performed a cost-benefit analysis of building controls in New Zealand, and concluded that the minimum direct cost of controls was $100 million annually with indirect costs of up to $200 million annually or 10% of the total cost of building in New Zealand at the time of the report[31]. The government established the Building Industry Commission (BIC) in February 1986, which wrote a number of reports culminating in their 1990 report "Reform of Building Controls." The primary objectives of the BIC were as follows:

(a) *to determine within a suitable economic framework the most appropriate legal and regulatory provisions for buildings and building construction and maintenance consistent with the public interest (including health, safety, and amenity aspects); and*

(b) *in those areas where it is considered that such objectives are best achieved through minimum performance standards, prepare an appropriate, simplified, uniform, performance-oriented national building code, which will bind the Crown*[22].

NZS 1900, which was the model bylaw at the time, was sometimes seen as a national building code, but since it did not "bind the Crown" it could only be implemented as a local bylaw[31]. The 1990 BIC report laid out the structure of the proposed New Zealand Building Code. The report recommended that regulatory intervention be limited to:

(a) *provisions safeguarding people's well-being where there is insufficient assurance that voluntary arrangements, such as market forces, self-regulation or self-interest will do the job;*

(b) *provisions protecting other people's property, including public property, that might be threatened by a building or building activity; and*

(c) *provisions related to the national interest, to follow clear Government direction or to reflect existing policies*[22].

The report lead to the New Zealand Parliment passing the Building Act 1991 and subsequently the Building Regulations 1992, which included the first national and performance-based building code in New Zealand. While New Zealand has been seen internationally as being one of the most successful countries at implementing a performance-based building code[14], it has not been a perfect transition. A lack of knowledge and methods to evaluate the ability of building designs to meet society's objectives has impaired the adoption of performance-based design practices and has resulted in some major failures, such as the leaky buildings discussed later in this chapter. To address these issues for fire risk, the fire engineering programme at the University of Canterbury was developed[32], where this research was conducted. One of the major sources of funding for the Canterbury fire engineering programme from the outset has been the New Zealand Fire Service Commission. The fact that the New Zealand Fire Service Commission continued to fund the Canterbury fire engineering programme through extremely difficult economic and social conditions in the 1990s[33] is a testament to the commitment in New Zealand to develop methods for performance-based building fire safety design.

1.3.3.2 1991-2004

Under the Building Act 1991, the Building Regulations 1992 were introduced, which included the New Zealand Building Code (NZBC) as the first schedule. The building code included 4 clauses on fire: C1 - outbreak of fire, C2 - means of escape, C3 - spread of fire, and C4 - structural stability during fire. The requirements of the building code can be met by following an Acceptable Solution as laid out in an compliance document (for fire, a single Acceptable Solution up until 2012 known as C/AS1[34]), by following an accepted verification method, or through an alternative solution using specific design methods. The Building Industry Authority (BIA) was created to manage the new building legislation. A method of resolving building-related disputes known as determinations was introduced, which was legislated in the Building Act 1991[35]. Determinations function as a sort of "case law" for alternative solutions[15] and provide building design practitioners with some guidance on what is required for an alternative solution to be granted consent.

The Building Act 1991 introduced the building consenting process, replacing building permits. This process gave the Territorial Authorities (TAs) the power to accept or reject building applications. The Building Act 1991 also introduced the requirement for compliance schedules if the building contained any active fire protection features, including sprinkler systems, smoke management systems, automatic doors, emergency warning and lighting systems, and any *"other mechanical, electrical, hydraulic, or electronic system whose proper operation is necessary for compliance with the building code*[35]*."* The compliance schedule specifies the inspection and maintenance requirements for the building. The compliance schedule is issued by the TA.

The new system was far from perfect, and many of the flaws were exposed by "leaky building" problems. While this issue was not directly related to fire safety, it is worth mentioning because the difficulties in implementing performance-based regulation in fire safety are comparable to weathertightness. Also, changes were made to the New Zealand building regulations as a result of the leaky building problems that affected other areas including fire safety. During the 1990s, a trend towards a 'Mediterranean' style of housing became popular among New Zealanders, with minimal eaves, exposed balconies, and monolithic claddings over timber frames[36]. The combination of these features, along with reduced quality control on junction management with flashing and other sealing methods, resulted in water entering the framework without being able to dry. Additionally, high quality interior finishes became desirable which required drying the framing timber from 24% to 16% moisture content. Kiln drying raised the cost of boron preservative treatment because it causes some of the treatment to evaporate, but it was thought that the lower moisture content would reduce the risk of wood rot and borer attack[37]. Therefore NZS 3602:1995 (*Timber and Wood-based Products for Use in Building*)[38] removed the requirement for radiata pine framing members to be treated providing they had been kiln dried to 18% moisture content or less, if they were not to be in contact with the ground or any position where the timber moisture content would exceed 18%. The combination of the water entering the building structure and the lack of treatment resulted in some framing elements rotting within two years of construction[39]. A large population of buildings were constructed using these practices and due to the nature of the leaky building problem the full cost is still uncertain, although it has been estimated at 11.3 billion NZD[40] or more than ten times the estimated annual cost of fire risk in New Zealand.

In 2002, the BIA appointed a Weathertightness Overview Group to investigate the leaky building problem in New Zealand. Their report pointed out a number of issues with the building control system in New Zealand at the time[39]. Cases where it was both too difficult and too easy to get alternative solutions (particularly in the case of cladding systems) through the consent process were discussed. One of the reasons given for this was a lack of skill among the TAs and building certifiers for evaluating alternative solutions. There was evidence that documentation of alternative cladding solutions did not provide details of the weathertightness design at the time of consent. Also, it was apparent that hubristic practices resulted in a lack of thorough building design and implementation review at the building consent, construction, and code compliance stages.

Implementing new fire safety system design practices could result in similar problems if the ability to quantify the changes in effectiveness is not developed. The change in fire risk may not be apparent until a sufficient population of buildings is available using the new design practices and until a sufficient number of fire incidents have occurred to create meaningful statistics, and by this time the cost to retrofit or rebuild flawed buildings to meet society's acceptable level of risk could be substantial.

1.3.3.3 2004-2012

Due in large part to leaky building problems[41], the Building Act 2004 was introduced, and the BIA was replaced with the Department of Building and Housing (DBH). The purpose of the DBH was to "consolidate building and housing regulatory and dispute resolution functions into one agency"[42]. The Building Regulations 1992 (including the building code) remained under the new Building Act.

The first review of the NZBC since it was enacted in 1992 was undertaken by the DBH in 2007[43]. The lack of quantification in the NZBC performance requirements was identified as a major concern, citing the previous determinations on multi-storey residential buildings. It was proposed that the NZBC be modified to provide explicit performance requirements as well as required design fires and fire scenarios that included requirements for design fire parameters, occupant response characteristics, and active and passive fire system properties.

1.3.3.4 2012

Following the recommendations of the 2007 review, substantial changes were proposed to the NZBC requirements for fire in 2010[44], and implemented in 2012. The four original clauses were replaced by six new clauses. The new clauses introduce quantitative guidance for tenability limits, internal lining performance, and firefighting access and water supplies, which is a departure from the previous building code. A new verification method C/VM2: Framework for fire safety was introduced which provides quantitative criteria for performing fire safety design, including design fires, pre-travel activity times, and movement speeds for calculating total evacuation time, as well as specifying the ten scenarios to be considered.

The changes allow the use of acceptable solutions C/AS1-6, the verification method C/VM2, or alternative design to meet the New Zealand building code requirements. However, alternative design is expected to be limited by the Building Consent Authorities (BCAs) to structures that are not "conventional buildings" such as towers, bridges, and tunnels. The acceptable solution method has been described by the DBH as analogous to a home cookbook for simple and generic building designs, while C/VM2 is compared to a restaurant chef in keeping with the food preparation metaphor[45]. The development of probabilistic methodology is considered in the realm of the master chef for the moment but it is seen as the future for fire safety design in New Zealand.

1.3.4 Fire safety system performance considerations in C/VM2

Currently, the verification method C/VM2 includes the following considerations for the effectiveness of fire safety systems. Section 3.1.1 which describes the parameters for pre-flashover design fires for design fire scenario 1, states:

> *For sprinkler protected buildings the fire is assumed to be controlled, i.e. constant heat release rate, after the sprinkler activates based on RTI and activation temperature.*

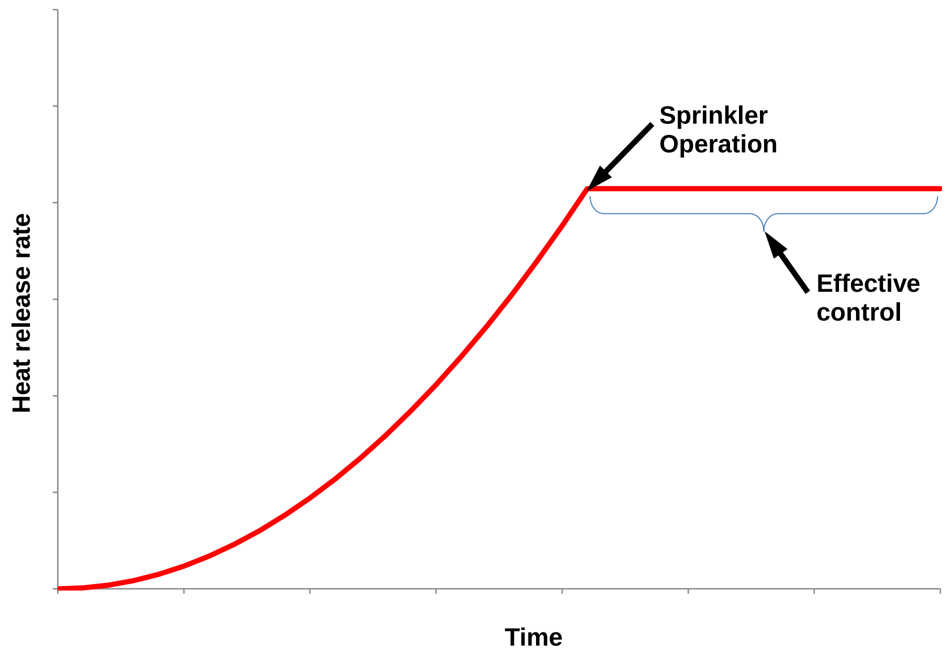

Figure 1.5: C/VM2 HRR curve for sprinkler fire control

This approach to estimating the effect of a sprinkler system on a fire is shown graphically in Figure 1.5, and is also described in the International Fire Engineering Guidelines[46].

Section 3.1.2 describes the parameters for post-flashover fires. It states:

It is expected that flashover will not occur in a sprinkler protected controlled fire.

Section 3.2, which describes the structural design fire *"based on complete burnout of the firecell with no intervention"*. The effects of sprinklers is included in the following statement:

The effects of sprinkler intervention on the structural design fire may be included by reducing the design fuel load energy density by 50% except in the case of primary elements whose failure could cause disproportionate collapse (e.g. isolated columns in a multi-storey building leading to sudden and complete failure) where there should be no reduction.

A number of general rules that should be followed when modelling fires to C/VM2 are included in section 4.0. The following address modelling the effectiveness of passive fire protection systems:

- *ii. Fire/Smoke doors with self closers are assumed closed unless being used by occupants. During egress, doors are assumed to be open for 3 seconds per occupant or for the duration of queuing whichever is the lesser.*
- *iii. Doors without self-closers are assumed to be open during the analysis.*
- *iv. Doors being used for egress are assumed to be half-width for ventilation flow calculation.*
- *v. Smoke control doors are assumed to have zero leakage area, except for a 10 mm gap at the sill.*
- *vi. Fire rated construction is considered to have no leakage.*
- *vii. Unrated walls are assumed to have leakage areas that are proportional to the surface area of the walls. Leakage area is equal to the wall area multiplied by 0.001 m^2/m^2.*
- *Fire rated doors that are not smoke control doors are assumed to have a 10 mm gap over the height of the door (nominally a 3 mm gap on four sides).*
- *Windows are assumed to break at either 500^oC or when the fire becomes limited by ventilation and the heat release rate reduces whichever occurs sooner.*

Section 6.3 discusses calculation of detection time for determining required safe evacuation time (RSET). It states:

> *The detection time shall be determined from the deterministic modelling conducted by the fire engineer. It is expected that the model used to calculate the detection time should use an appropriate fire model for this analysis that incorporates a ceiling jet algorithm which includes the upper layer or a CFD code that solves for the velocity and temperature directly.*

Scenario 10 is intended to demonstrate the effect of a fire safety system failing. The description is given as:

> *Test the robustness of the design by considering the design fire with each key fire safety system rendered ineffective in turn.*

It is stated that *" only the FED(CO) criterion is to be met"*. The definition of key fire safety systems is given as:

> *smoke management systems, and fire and/or smoke doors or similar fire closures. Fire sprinklers and automatic fire alarms installed to a recognised standard are considered to be sufficiently reliable, that the robustness test described here need not be applied.*

1.4 Key documents and standards related to specific fire safety design

A number of documents have been published which are pertinent to probabilistic methods for performance-based fire engineering. This section discusses three of them and the information that they present regarding the consideration of fire safety systems in probabilistic risk analysis.

1.4.1 International Fire Engineering Guidelines

The International Fire Engineering Guidelines (IFEG)[46], endorsed by Australian (the Australian Building Codes Board), New Zealand (the Department of Building and Housing), American (the International Codes Council), and Canadian (NRCC-IRC) organizations, discusses appropriate methods of analysis for fire engineering design. The IFEG is split into four parts.

Part 0 has been written separately for all four of the signatory countries, and discusses the regulatory environment in each country. Part 1 describes the process that is recommended for fire engineering, splitting it into five stages. The first step is the Fire Engineering Brief (FEB), followed by analysis, evaluation of results, conclusions, and report preparation. Different approachs are described, including comparative or absolute, qualitative or quantitative, and deterministic or probabilistic. Part 2 describes simple methods for analysis which are mostly deterministic.

Part 3 includes a limited amount of fire engineering data. Short sections on smoke control and suppression system effectiveness are included, as well as a section on spread through separations. Data included in these sections is very limited and the spread through separations section does not discuss the probability that the separation may be compromised before ignition. Qualitative methods are usually limited to small deviations from the prescriptive solutions, sometimes using the "Delphi" approach where a panel of experts are used to evaluate the acceptability of the design.

1.4.2 PD7974

The British Standards Institution Published Document 7974[47] is a code of practice for the *"application of fire safety engineering principles to the design of buildings"* and is comprised of eight subdocuments (including PD7974-0). PD 7974-7:2003 provides information specific to probabilistic risk analysis, including principles, techniques, and data. PD7974-7:2003 provides guidance for estimating fire safety system effectiveness for probabilistic risk assessment purposes, but it also provides the following caveat:

> *"The application of PRA can be severely limited by data availability. Deterministic and prescriptive fire engineering techniques have typically bridged the gaps between what data are readily available and what are absent by taking a conservative approach. The same approach cannot be readily used in PRA studies."*[47]

Guidance from PD7974-7:2003 on individual systems will be discussed in the pertinent sections of the following chapters.

1.4.3 ISO documents

Subcommittee SC4 of the International Organization for Standardization (ISO) technical committee TC92 is tasked with developing standards and guidance for fire safety engineering[48]. Documents produced by this subcommittee include Technical Report 13387:1999 which has 8 parts, Technical Specification 16732:2005 which provides fire risk assessment guidance, and Technical Specification 16733:2006 which describes design fire scenario and design fire selection.

1.5 Defining effectiveness

The effectiveness of fire safety systems have been defined and categorized with different approaches. The nomenclature defined by Thomas[49] will be used for this study. For a system to be effective, the first requirement is that it is in place, operational, and for active systems, ready to respond if a fire occurs. *Reliability* will be used to describe this condition of the system. Another term that has been used is *operational reliability*[50]. The reasons why a system may not be operational or ready to respond can vary from being willfully disabled, a damaged component that is not able to operate, or that the system is down for maintenance, among others. *Availability* is a term that is used to describe the inability of the system to respond due to inspection, maintenance, testing, or modification work[51]. For the purposes of this research, reliability will be used to describe the state of the system prior to the fire, and as such is not considered temporally.

Once a system is in place and ready to respond to a fire, it must be able to perform the function that it is intended for. The term *efficacy* will be used in this study for this purpose. Another equivalent term that has been used in other studies is *performance reliability*. Efficacy is used in the model to estimate how well systems affect fire development temporally in comparison to their design intent. In the model, efficacy depends on the specific fire scenario being considered. For example, fire location, fire heat release growth, and room geometry may influence the efficacy of a sprinkler system, by affecting the time that the sprinkler system activates. In turn, the available water supply pressure will determine if sufficient water is available to suppress the fire.

Effectiveness is a measure of the overall performance of the system in fire. Reliability and efficacy are multiplied to estimate the system effectiveness.

1.6 Uncertainty

There are many different sources of uncertainty in fire safety design, and many may be nearly impossible to quantify. Different sources of uncertainty become important depending on whether prescriptive-based or performance-based building regulations are used. There is little uncertainty in acceptable building design under prescriptive-based regulation because the acceptable method is specified directly in the regulations, although there can be linguistic uncertainty due to interpretations and there also can be uncertainty when the building occupancy, purpose, or design do not exactly fit the categories in the regulations. The main uncertainty in prescriptive-based codes is in the intent of the code because it is not generally specified. Performance-based regulations reduce the uncertainty in the intent of the code but increase the uncertainty in the ability of a specific building design to meet the requirements of the regulations. This must then be estimated by modelling, comparison, expert judgement[52,53], and other means.

Several studies have considered uncertainty for performance-based fire safety design. Notarianni[54] included the effects of uncertainty in building geometry, ventilation, weather, building materials, room of origin, fire parameters, combustion products, and chemistry on the time to untenability using Monte Carlo runs of the two-zone model CFAST. Notarianni also looked at a municipal model for calculating the benefits of residential sprinklers, where sprinkler effectiveness was modelled by using a sprinkler reduction factor on premature deaths due to fire.

Lundin[55,56,57,58] studied methods of quantifying model uncertainty in smoke temperature and layer height predictions from zone models using the CFAST model. Frantzich[59] developed a QRA method for fire safety that considered uncertainty and applied it to a health care facility and a hotel[60].

Siu[61] discusses uncertainties in deterministic fire models. Siu and Apostolakis[62] discuss combining diverse information sources including, direct data, indirectly applicable data, and expert opinions for suppression effectiveness using Bayes' theorem.

The large number of taxonomies for uncertainty indicates that there is a large degree of uncertainty in even classifying uncertainty[63]. The classification system considered in this research was developed by the Danish Energy Agency for the purpose of QRA[55]. This system classifies uncertainties as resource uncertainty, assumption and decision uncertainty, model uncertainty (commonly known as epistemic uncertainty) and input uncertainty (also known as aleatoric uncertainty).

Resource uncertainty includes big-picture factors such as uncertainty in project management and quality control, the quality of available research, and available analytical methods. For example, a certain type of sprinkler might be specified by the designer, but if a sprinkler with different response parameters is installed by mistake then the sprinkler will not respond as predicted by the designer. Resource uncertainty is not generally considered in this study and is difficult to quantify but it can significantly influence the performance of a fire safety design.

An example of resource uncertainty in sprinkler system effectiveness occurred in Palm Beach, California, when a contractor was found to be installing sprinkler heads that were not connected to the water supply[64]. Some sources of resource uncertainty such as the above example are addressed by the requirements of standards for specific fire safety systems.

Decisions and choices made in selecting models and assumptions include uncertainty. For modelling fire, a variety of models are available, ranging from simple correlations to zone and field models. Decision uncertainty can become more of an issue with a more complex model. A simple hand calculation based on one input parameter will have less decision uncertainty than a more complex zone or field model. An example of decision uncertainty within a zone fire model is the choice of plume air entrainment and ceiling jet submodels. The a priori simulations of the Dalmarnock fire test[65] demonstrate how decision uncertainty can affect the outcome of a prediction when there are a large number of degrees of freedom in the model. Several modellers were given a set of input data and produced substantially different results using the same two computer fire models, FDS and CFAST. The new NZBC fire safety clauses and verification method C/VM2 address some of the decision uncertainty in fire safety design by specifying some model input parameters; for example, tenability, design fire, and evacuation parameters are defined. However the choice of model is still left to the designer.

Epistemic uncertainty is the uncertainty in the modelling processes employed, and is a function of the model. A key consideration for the selection and use of a fire model is the accuracy of the model. However, the principles of "consistent level of crudeness"[7,32] apply: if the certainty in the input parameters to the model is low, then the accuracy of the model itself is less important.

Aleatoric uncertainty considers natural variability. Aleatoric uncertainty depends on the situation being considered. Some of the input parameters for a specific fire that is being reconstructed will be known with much more certainty than in the case of a building fire safety design QRA. For instance, the point of origin and geometry of the room of origin may be known in a reconstruction, and depending on extent of damage, the relevant material properties of the fuel and surrounding materials can be measured. In the case of building fire safety design, the geometry of the building and the contents can change over the lifetime of the building and thus should be factored into the modelling scenario.

Typically fire models are verified by comparing model predictions with experimental measurements. The goal of experiments is to minimise the aleatoric uncertainty, i.e. control the input parameters as closely as possible. In this situation, the fit of the model to the experimental data can be improved by increasing the complexity of the model; for example, by going from a zone model to a field model or from a simpler field model to a more refined field model. Increasing the complexity of the model allows it to be adjusted to fit the results more closely. However, this is not representative of the use of a model within a design or reconstruction context. In order to provide benefit to society, a fire model must either be able to provide additional information or insight into a real-world fire scenario beyond what can be observed, whether it is to reconstruct a past fire or to consider risks from future fires. Any real scenario has less information available and less control of input parameters than an experimental fire; that is, there is more aleatoric uncertainty. The verification data provides useful information on the model uncertainty, because aleatoric uncertainty is minimised. If the aleatoric uncertainty in the scenario that is being considered is greater than the model uncertainty, then the accuracy of the model is likely sufficient for the intended purpose. An example of this concept is presented in Chapter 5 when estimating the first sprinkler activation time.

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CHAPTER 2

A REVIEW OF FIRE RISK MODELS AND AN INTRODUCTION TO B-RISK

This chapter contains a review of existing fire risk models with an emphasis on their capabilities to include the effects of fire safety systems on fire. The project which this research was conducted under and the new risk-informed fire safety building design tool B-RISK which was developed as an outcome of the project are described.

2.1 Existing fire risk models

Quantitative, deterministic tools for fire engineering have developed substantially in recent years, ranging from simple analytical formulae, to experimental methods, to computer models. Computer models range from zone models (such as the Consolidated Model of Fire and Smoke Transport or CFAST, developed by the National Institute of Standards and Technology or NIST in the US, and BRANZFire developed by the Building Research Association of New Zealand) to field models (such as the Fire Dynamics Simulator or FDS developed by NIST, and FireFOAM developed by FM Global). Probabilistic models are also available, including the @RISK package which is not specific to fire but can be applied to any deterministic model. Some tools considering both probabilistic and deterministic dimensions of fire risk management, including FIERAsystem and FireCAM developed by the National Research Council of Canada's Institute for Research in Construction (NRCC-IRC), FIRE-RISK developed in Australia, and CRISP developed in the UK have been developed but are not expected to be publicly available in the near future. None of these probabilistic-deterministic models specific to building fire risk were available at the time this research was conducted and it was unclear if their development would be continued. This section discusses how fire safety system effectiveness is handled in the FIERASystem, FireCAM, CESARE-Risk, and CRISP models, and includes a list of other previous fire risk models.

2.1.1 FIERASystem and FireCAM

The National Research Council of Canada (NRCC) has developed two tools for demonstrating the ability of designs to meet performance-based regulations: the Fire Evaluation and Risk Assessment System (FIERAsystem) and the Fire Cost Assessment Model (FireCAM). These tools have both been described as probabilistic-deterministic[1]. FireCAM was designed for residential and office buildings, and FIERAsystem is targeted at light industrial buildings[2].

FireCAM considers six design fire scenarios in the room of fire origin: smouldering, non-flashover, and flashover fires; each with the door open or closed[3]. Each design fire is assigned a probability. A single zone model is used to calculate the spread of fire and smoke.[4]. For detection purposes, the times of smoke detector and sprinkler operation are estimated to coincide with the temperature in the compartment rising by 20^{o}C and reaching 100^{o}C, respectively. Sprinkler system effects on the fire are handled as follows:

1. *The installation and effective operation of a sprinkler system during a fire will extinguish the fire, resulting in minimal damage to the building and no loss of life*
2. *For the small probability that the sprinkler system fails to extinguish a fire, the fire is assumed to burn as if there is no sprinkler system installed*
3. *Smouldering fires will not activate sprinklers as they do not generate enough heat*[5]

Factors for the reliability and effectiveness of the sprinkler system are estimated. Sprinkler system reliability for non-flashover fires is estimated to be 25% of that of flashover fires, presumably because of the number of fires that would be too small to operate the sprinkler system. The probabilities for the flashover and non-flashover are modified by the sprinkler reliability and effectiveness factors. The sprinkler system is assumed to have no effect on smouldering fires[6].

Passive feature effectiveness is considered in the probability that the door to the fire compartment is open or closed and with the fire resistance rating of the walls[5]. There was no mention found of considerations for smoke management systems.

FIERAsystem is comprised of many submodels which could be run individually or collectively as a hazard or risk analysis. Fire development scenarios for liquid pool fires, storage rack fires, and t^2 fires are included. A two-zone model is used for smoke spread[7,8]. The FIERAsystem suppression effectiveness model[9] is a simple model with a single value ranging from $\eta = 0$ to $\eta = 1$. The model is shown graphically in Figure 2.1. $\eta = 0$ corresponds to a automatic suppression system that does not affect the fire (the heat release curve and all other functions remain the same as if the suppression system did not activate). If $\eta = 1$, the suppression system limits the HRR to the value at the time of activation. The suppression effectiveness model does not affect a decaying HRR below the HRR at sprinkler activation, to prevent increasing the HRR in these circumstances. The modified heat release rate is then used to recalculate the thermal radiation heat flux, fire plume temperature, and flame height.

Detection devices are assigned a reliability value which represented the probability that each would respond to the fire at the calculated time[10]. Calculated activation times were assumed to be a mean activation time and normal probability distributions were assigned for actual activation times. Local alarms, sprinklers, heat detectors, and smoke detectors were all assigned a standard deviation of 10 seconds.

FIERAsystem also included a Boundary Element Failure Model which apparently modelled the failure of passive features due to fire[11]. It is unknown how elements that are compromised or open at the beginning of the fire were accounted for. It also appears that the effects of smoke management systems were not included[12].

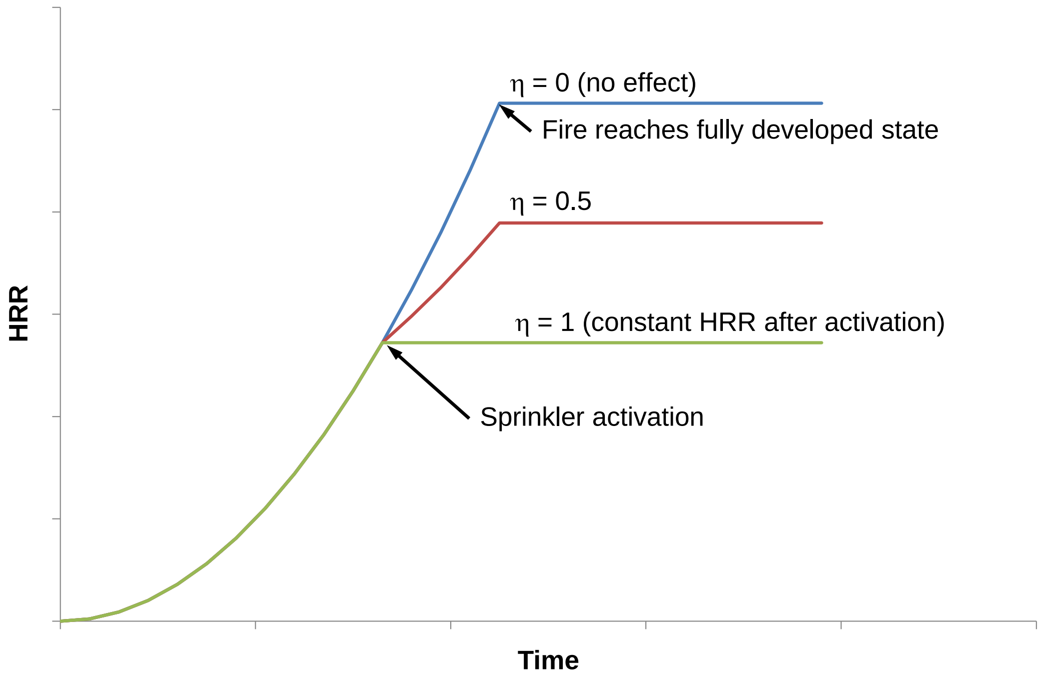

Figure 2.1: The FIERAsystem sprinkler effectiveness model. Taken from Torvi et al[9].

2.1.2 CESARE-Risk

The Centre for Environmental Safety and Risk Engineering (CESARE) in Australia developed a tool known as CESARE-Risk or FIRE-Risk that used a one-zone model similar to FireCAM. CESARE-Risk was not available at the time of writing, but from a review of available literature it appeared that CESARE-Risk did not consider suppression or smoke management. There was some discussion of the failure of passive elements[13,14,15,16].

CESARE-RISK included Monte Carlo analysis of a matrix of 384 runs, with variations including three fire types (smouldering, flaming, and flashover), three growth rates for each fire type, four ventilation states for the room of fire origin (door and window open and closed), four ventilation states for further fire spread (apartment of fire origin and stairwell doors open and closed), and occupants awake or sleeping[17]. Continuous distributions were replaced by equivalent 3 point discrete distributions. This approach is used in the fire growth, fire brigade intervention and human response models. Fire spread beyond the room of origin is not considered in the time dependent part of CESARE-RISK.

2.1.3 CRISP

A fire risk assessment model developed by the Building Research Establishment (BRE) in the United Kingdom is known as CRISP II, or Computation of Risk Indices by Simulation Procedures[18]. CRISP II is described as object-oriented zone model, where burning items gas layers, people, vents, smoke detectors, and walls are all considered as objects[19]. There does not appear to be any mechanism for accounting for automatic suppression or smoke management. Passive elements such as doors and windows are considered as vents. Fire spread between items is not considered in CRISP[20].

2.1.4 Other models

Hall and Sekizawa[21,22] provide a thorough summary of several fire risk modelling approaches, including a synopsis of the calculation methodology and data sources employed by these models. A number of models have been developed that use a probabilistic network approach to predicting fire and smoke spread. Examples include those by Elms, Buchanan, Dusing, and Platt[23,24], Ling and Williamson[25], and Fitzgerald[26]. Event tree fire risk models have been described as early as 1980, using both quantitative[27] and qualitative[28] approaches.

PD7974-7:20003 also discusses event tree, fault tree, and fire spread network approaches[29]. Event trees consider the probability for a sequence of discrete events to occur, usually with binary successful or failed outcomes for each event (as an example, a sprinkler either controlling the fire or not controlling the fire). The probabilities for each event outcome are multiplied to estimate a probability for specific event sequences or scenarios to occur, which is then multiplied by the expected consequences. A typical event tree is shown in Figure 2.2. The event tree approach was used in the case studies discussed later in this chapter.

A fault tree is used in fire risk analysis to determine the overall reliability of a system from component data, and is discussed in more depth in Chapter 3.

Several models have been developed for fire risk analysis in the nuclear industry, including COMPBRN[30] and others[31,32]. A method of evaluating fire risk in telecommunications facilities known as the Central Office Fire Risk Assessment (COFRA) procedure was developed to consider business interruption risk[33].

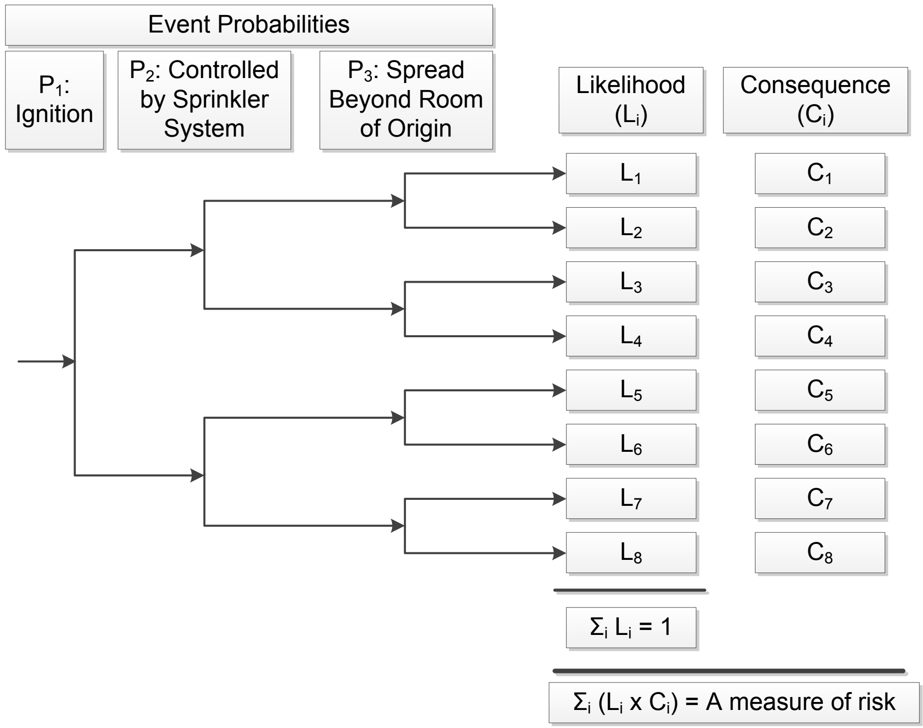

Figure 2.2: Typical event tree for 3 events, with event probabilities P_1 - P_3. Successful sprinkler fire control is represented as the second event.

2.2 MSI building safety design fire tool project

This research is part of a larger project involving the Building Research Association of New Zealand (BRANZ) and the University of Canterbury to support risk-based fire engineering in New Zealand, funded by the New Zealand Ministry of Science and Innovation (MSI) (formerly known as the Foundation for Research, Science and Technology), the New Zealand Building Research Levy, and the New Zealand Department of Building and Housing (DBH). The overall project builds on fire safety modelling capability developed in New Zealand with the goal of producing a tool to support future risk-based building fire safety regulations and design. Figure 2.3 demonstrates how this project on fire safety system effectiveness fits within the larger overall scope.

The tool uses the capabilities developed for the BRANZFire fire physics model as the fire and smoke spread engine. A new design fire generator is being developed

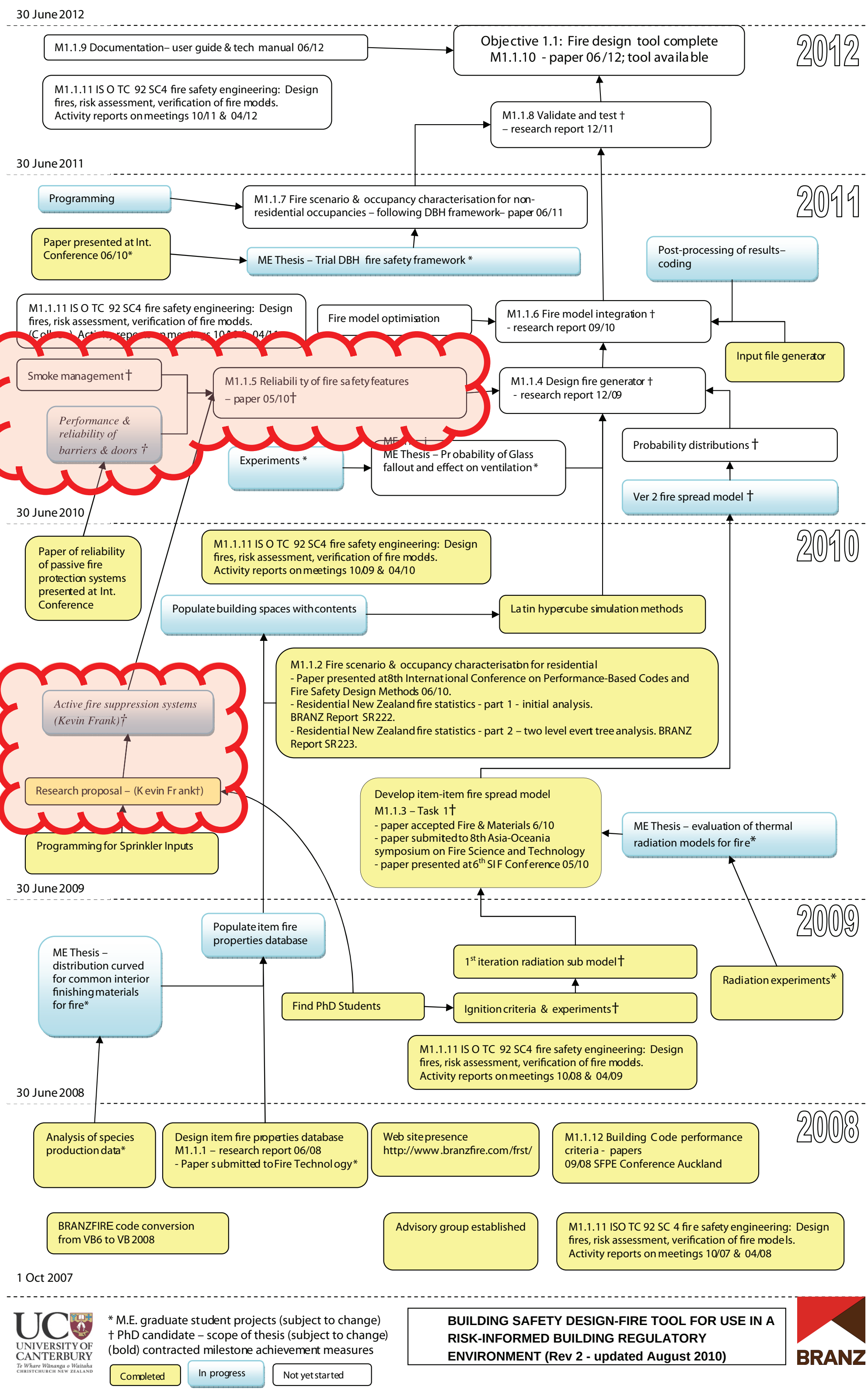

Figure 2.3: Flowchart showing an overview of the building safety design-fire tool for use in a risk-informed regulatory environment. Taken from BRANZ.

by other researchers to create probabilistic room contents design fire scenarios. A module places room contents probabilistically with rules to make the item locations realistic; for example, a piece of furniture will not be placed to block the doorway into a lounge. Of the items placed in the room, one is randomly chosen to be the first item ignited. An item-to-item fire spread model has also been developed by others as part of this project, to continue the fire development as it spreads to multiple items.

The MSI project at the time of this research is only considering the design fire or fire development aspect of fire safety. In terms of fire engineering outcomes, the tool is focussed on estimating the available safe egress time (ASET), or the time that is available from the initiation of the fire until the building becomes untenable for occupants. This does not consider the human behaviour and response to fire, for both occupants and Fire Service responders. The tool may be extended to these aspects in the future, by integrating with other tools that have been developed for these aspects such as EvacuatioNZ[34] for occupant behaviour and the Fire Brigade Intervention Model[35] (FBIM) for fire service responders.

The goal of this research as a part of the larger project is to develop the ability of the new tool to model the effects of fire safety systems on the fire and smoke development and spread in a risk-informed manner. Other effects of the system such as occupant notification are not considered. The probabilistic nature of the new tool allows fire safety system effectiveness uncertainty to be considered. Appropriate input distributions for fire safety systems in the new model are discussed, as well as methods for analysing the sensitivity of the model output to the relevant input parameters. Note that uncertainties will depend on the scenario being considered, so results from this research should not be taken out of context for other applications.

2.3 Description of B-RISK

B-RISK samples input parameter distributions to create Monte Carlo input files and then uses a deterministic model to estimate the spread of fire and smoke in buildings. Some features are then available to evaluate the individual deterministic or combined probabilistic output. B-RISK has the capability to output model geometry, layer height, and vent flows to Smokeview (a fire simulation visualisation software developed by NIST) for visualisation.

2.3.1 Deterministic fire and smoke spread model

A design fire generator with item-to-item fire spread capabilities has been developed to model the spread of fire[36]. Alternatively, global t^2 or t^3h fires can be specified. The HRR time history must be specified, either for the entire fire or for individual items if the item-to-item design fire generator is used. A burning rate enhancement option is available to simulate the effects of the compartment on the HRR. A two zone model is used to estimate smoke spread in up to ten compartments[37].

For the item-to-item design fire generator, a radiative heat transfer model is used to estimate the heat flux that items not yet ignited receive from burning items[36]. The flux time product (FTP) model is then used to calculate when the item has received enough energy to ignite[38]. Two mechanisms are used to estimate secondary ignition: radiant heat from burning items igniting vertical surfaces and radiant heat from the upper layer igniting horizontal (top) surfaces on unburnt items.

In early B-RISK versions, one of 2 submodels could be chosen for axisymmetric plume entrainment; one developed by Delichatsios[39] and one by McCaffrey[40]. The current version only allows the Heskestad axisymmetric plume entrainment model. Entrainment models developed by Harrison[41] are implemented for spill plumes. An option for a "disturbed plume" is available which doubles entrainment for plumes subjected to external air movement.

2.3.2 Systems in the deterministic model

The deterministic fire physics engine has considerations for the effects of sprinkler systems, passive features, and smoke management systems. Either Alpert's correlations[42] or the NIST JET model[43] can be used to calculate ceiling jet temperature and velocity for heat detectors. Alpert's correlations do not consider the effect of a hot layer and have been shown to overpredict heat detector activation times in circumstances where a layer can form[44]. The thermal dectector response model by Heskestad and Bill Jr.[45] is then used to estimate sprinkler activation.

The effect of sprinklers on the heat release rate can either be modelled as having no effect, a "control mode" where the heat release is held constant at the value given when the first sprinkler activated, or approximate suppression using the model developed by Evans[46].

The status of passive fire compartmentalisation features can be considered during the fire by opening or closing vents. Flows through vents are calculated. A description of the horizontal and vertical vent flow models can be found in the BRANZFIRE technical reference manual[40], and are based on the CCFM.VENTS and VENTCF2A algorithms developed by Cooper and Forney[47,48]. Vents are assumed to open or close over 2 seconds by a linear increase or decrease in the width.

Fire resistance ratings are based on the standard fire severity test. A method for estimating the actual time to passive element failure under real fire severity conditions, developed by Nyman[49], has been incorporated in the deterministic model. The model was developed from testing on light timber frame (LTF) and light steel frame (LSF) passive assemblies. A glass fracture model by Parry[50] is included as well, but does not predict fall out which is more important in terms of the integrity of the compartment. Recent work by Wong[51] has been completed which provides a probabilistic model for glass fallout, based on a limited number of window configurations. Since the scope of this research does not include the effects of fire on passive building elements, there is no further discussion of these features in this dissertation.

Two features are available for modelling the response of smoke management systems, in addition to the vent and heat detector algorithms listed above. If a smoke detector is used to activate the system, Heskestad's detector model in combination with the smoke concentration model by Davis et. al.[52] can be used to predict the time of activation. Pressurisation or extraction by mechanical means (fans) can also be considered, although the fan can only be located in one layer. Either a specified flow rate or a fan curve which calculates the flow rate based on the pressure differential can be used. If a layer is thin the model will consider the "plugholing" effect where both layers are drawn through the fan.

A more detailed discussion of how specific systems are considered by the deterministic model is included in pertinent chapters where required.

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CHAPTER 3

STATISTICS AND OTHER EXISTING MEASURES OF SPRINKLER EFFECTIVENESS

3.1 Introduction

As noted in the New Zealand and Australian risk-informed fire safety building design case studies discussed in Chapter 11, one of the most influential factors on fire risk is the effect of sprinkler systems on fire development. Typically for design purposes, an assumption of the effect of the sprinkler system on the fire's HRR will be made. A typical case is the control assumption discussed for C/VM2 in Chapter 1. This assumes that the sprinkler system operates reliably and is able to perform the job it was designed for. In reality, this may not always be the case, and can be accounted for in probabilistic risk-informed fire safety design. Sprinkler performance in fires may depend on the following factors:

- age and deterioration
- inspection, testing, and maintenance
- standards and technology available at the time of design
- modifications
- changes in building use or hazard being protected
- building design

- other building systems, such as heating and ventilation
- water supply changes

among others.

By examining the performance of sprinkler systems and sprinkler system components in past fires, estimates of future sprinkler system effectiveness can be made. However, it is difficult if not impossible to determine the effect of a sprinkler system on real fires in terms of heat release rate so a number of other criteria have been used, such as:

- fire containment to room of origin
- number of sprinklers activated
- amount of damage to structure and property
- required amount of fire service intervention
- occupant injuries or fatalities

The differences in these criteria make it difficult to apply the reported sprinkler effectiveness probabilities to fire risk modelling. The use of these criteria in the studies identified in the literature is discussed in Section 3.3.

A number of studies have been published which provide information on sprinkler system effectiveness. Since automatic sprinkler systems were originally invented and developed in the 1800s[1], there has been debate as to how effective they are. An early reference to estimates of sprinkler effectiveness can be found in the Preliminary Report of the New York State Factory Investigating Commission, which was released in 1912 following the Triangle Shirtwaist fire. This report stated that[2]:

> *"Testimony as to the efficacy of sprinkler systems varies, but the lowest estimate of their proper working is 75 per cent and the highest 95 per cent."*

It is unknown what information this testimony was based on. As the 20th century progressed, several other organisations recorded information on the operation of sprinkler systems. This chapter reviews the information currently available from studies on sprinkler system effectiveness in the context of using this information for risk-informed building fire safety design. This review does not generally attempt to judge the value of existing studies as that judgement will depend on the context of the approach to obtain the data and the data application. Some information from Chapter 4 which describes sprinkler effectiveness estimates from recent NZFS data is included for comparison.

3.1.1 Definitions

As discussed in Chapter 1, "reliability" is defined as the probability that a sprinkler system will activate and supply water to a fire demand. "Efficacy" is defined as the probability that the sprinkler system will affect the development of the fire as specified in the system design objectives, given that it operates. "Effectiveness" is a term describing the overall performance of the sprinkler system, combining both the reliability and efficacy. These definitions have been used in other studies on sprinkler systems, such as those by[3], "Availability" describes the probability that the system will not be out of service for inspection, testing, or maintenance, and is included in reliability.

This review does not consider the potential for sprinkler systems to fail when there is no fire present. Such situations may include rupture due to freezing or mechanical damage leading to water damage, or activation in non-fire conditions. These types of failure are not generally directly considered in a building fire risk analysis, but they may be relevant for other purposes, such as a cost/benefit analysis for installing specific fire protection systems.

Sprinkler system reliability and effectiveness as defined do not directly translate to impact measures; for example, reduction of property damage or a reduction of fatalities. They are a measure of the ability of the sprinkler system to respond and to meet the design objectives, respectively. As an extreme example, a "100% effective" sprinkler system would not equate to a 100% reduction in loss, because a fire must be present and reach sufficient size to activate the sprinkler system as designed and thus there will always be a measure of loss in a sprinklered fire. Impact measures are discussed later in this chapter.

3.1.2 Types of sprinkler effectiveness studies

Two general approaches have been used in previous studies taken to quantify sprinkler effectiveness:

1. Component-based (fault tree)
2. System-based (incident data)

The component-based approach builds an effectiveness estimate for a system from individual component data. The system-based approach estimates the effectiveness of the entire system directly from past performance in actual fire incidents. For design purposes, either approach have been used with data obtained from already installed systems or "expert judgement" estimates (which are not further discussed in this review of sprinkler system effectiveness studies) if data was deemed to be lacking or insufficient. This review will compare the effectiveness estimates obtained from component-based approaches and system-based separately, and subsequently attempt to reconcile them to compare differences and similarities between the values obtained through each approach.

3.1.3 Other sprinkler effectiveness review studies

Sprinkler effectiveness reviews have been conducted by Smith[4], Richardson[5], Bukowski et al[6], Feeney[7], Koffel[8], and Sakenaite[9]. Several studies combine a review of other sources and new data, including Finucane and Pickney[10], Budnick[11], and Gravestock[12].

3.2 Component-based studies

Component-based studies of sprinkler performance use estimates of individual component reliability and combine them using some approach, typically a fault tree, to obtain an estimate of the system effectiveness. These studies typically provide a reliability estimate for the system only since it is difficult to attribute efficacy to individual components. A notable exception was completed by Gravestock[12], who combined estimates of sprinkler efficacy in smouldering, flaming non-flashover, and flashover fires with a reliability fault tree to estimate an overall effectiveness.

Component-based reliability data is either reported as a failure probability per demand or a failure rate for a unit time. The following formula is used to calculate per demand probability from a failure rate:

$$P(per\ demand) = 1 - e^{-\lambda t} \tag{3.1}$$

where λ is the failure rate and t is the time between maintenance, inspection, or replacement. This equation is found in various sources (for example, Lees[13]) and can be used to convert the following component data from failure rate to failure probability per demand, but it assumes the failure rate is constant over time and will depend on the time period used so it is specific to each application. Thus, the data here is reported in the same units and type as originally discussed in the literature.

Component-based reliability probabilities can be combined to estimate system reliability through fault trees. A simple fault tree is shown in Figure 3.1. Individual component reliability probabilities can be combined, or if data on unique failure modes for individual components is known then they can be included as well. Note that the equations shown for the AND and OR logic assume that the reliability probabilities are independent, which may not always be a realistic assumption if there are significant common-cause failure modes. The fault tree used for a specific sprinkler system will depend on the components that are present in the system.

3.2.1 Sprinkler system component data

Table 3.1 shows the identified studies that provide sprinkler system component data. Component data has been classified as related to sprinkler head operation (Table 3.2), sprinkler piping (Table 3.3), valves (Table 3.4), pumps (Table 3.5), water supplies (Table 3.6), and miscellaneous components (Table 3.7).

Moelling et al[14] evaluated sprinkler systems in four nuclear power plants using a fault tree approach. Failure was considered to be system failure to operate on demand, and the performance of the sprinkler system after operation was not

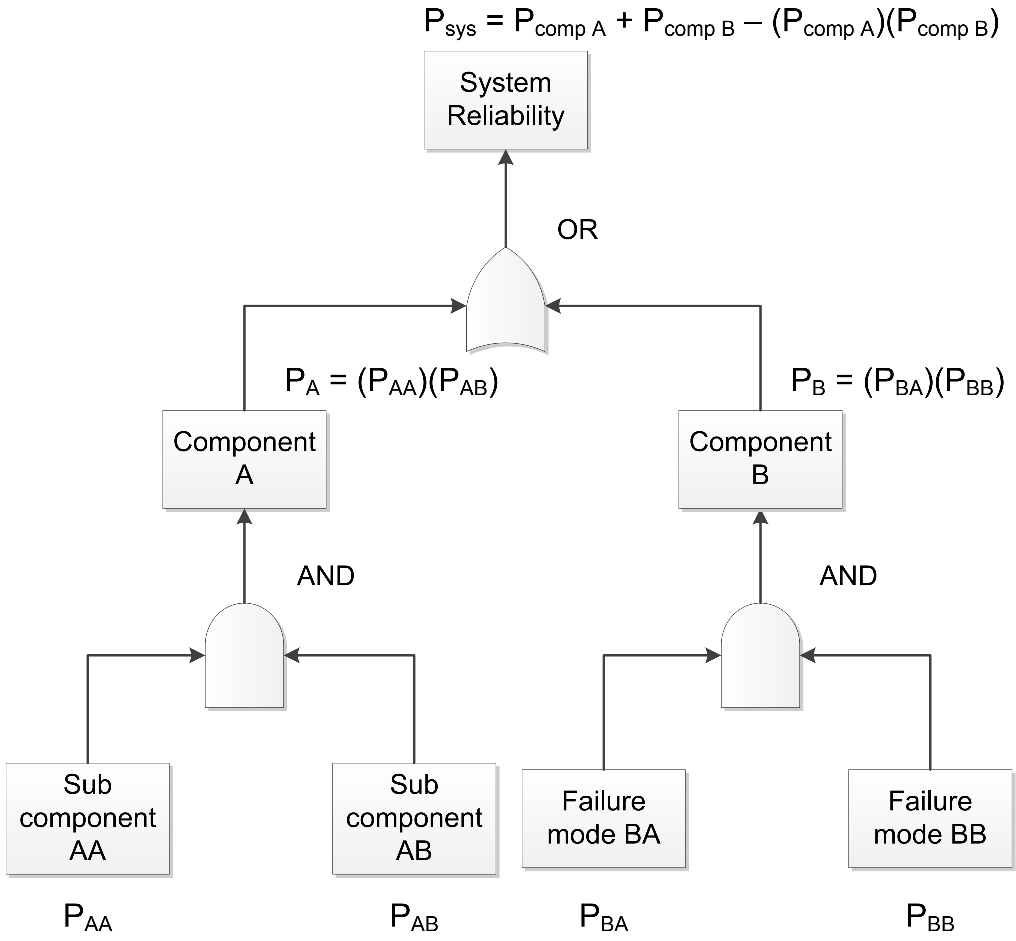

Figure 3.1: A basic example of a fault tree. The equations shown assume the probabilities are independent. For the sprinkler system application, included components could be water supplies, sprinkler heads, piping, valves, or other components. Additional components and sub-component levels can be added as required.

considered. While specific information for each of the sprinkler systems was not presented, probabilities for 8 failure modes were included. The source of the probabilities used was not made explicit. Two of these were human-based: inadvertently closed valves and failing to trip a manual release. System reliability was found to be most sensitive to the probability of an inadvertently closed valve and the time between inspections.

Finucane and Pickney[10] and Nash and Young[15] provided similar failure rates for multiple sprinkler system components, apparently both sourced from 1972 UK

Atomic Energy Authority data.

Budnick[11,16] collected inspection, test, and maintenance failure data on nine types of component from six sprinkler systems in one facility.

Hauptmanns et al[17] employed the most comprehensive fault tree of the reviewed studies with 60 possible contributing events. Failure probabilities for each event were assigned to a class ranging from 1 to 6 corresponding to an order of magnitude failure probability from 0.1-0.8 to 0.00001-0.0001, respectively. For the specific system considered in the analysis presented in Hauptmann's paper, failure probabilities of $7.1\text{x}10^{-4}$, $5.5\text{x}10^{-2}$, $6.4\text{x}10^{-5}$, and $3.1\text{x}10^{-3}$ were estimated for the sprinkler piping network, alarm valve station, water supply, and pumps, respectively.

Ronty and Keski-Rahkonen[18] looked at maintenance records from sprinkler systems in Finland to estimate sprinkler reliability. The focus of the study was sprinkler systems in nuclear facilities but the authors concluded that there was an insufficient amount of data available from Finnish nuclear facilities so they also collected data from non-nuclear facilities. The values listed in this paper were obtained from the non-nuclear facilities, and Ronty and Keski-Rahkonen note that this data should be used with caution due to *"insufficient critical analysis of the data"*.

Watanabe[19] estimated the failure rates of sprinkler subsystems and components from the maintenance records of 97 sprinkler systems in Japan. These systems included a total of 121,991 sprinkler heads and 707 piping arrays. Overall sprinkler reliability, capability (efficacy), availability, and effectiveness were estimated at 98.9%, 99.9%, 99.3%, and 98%, respectively.

Moinuddin et al[20] surveyed sprinkler systems in 23 high-rise office buildings in Australia, out of a total of 60 buildings whose staff was contacted for information. Moinuddin observed that the buildings that did not participate may have had a lower standard of maintenance than those that did. The data was used in a fault-tree analysis to estimate sprinkler system reliability for upfeed (water supplied from the base of the building) and downfeed (water supplied by gravity from above) configurations.

Offshore Reliability Data (OREDA) is an organisation that collects reliability data for the petroleum industry. Data is collected on several components that may be relevant to specific sprinkler systems, including deluge valves and pumps[21].

The focus of the dataset is on offshore oil and gas installations which may not be applicable to onshore building sprinkler systems.

Brammer[22] conducted a study into the reliability of secondary water supplies as required by the New Zealand sprinkler standard NZS:4541(2007)[23] in some circumstances. He also provided reliability estimates for single sprinkler system water supplies. A case study for the water supply system for Adelaide, Australia was included.

Source	Country	Source of data	Application focus
Watanabe[19]	Japan	Maintenance records	Japanese buildings
Moelling et al[14]	US	Unknown	US nuclear installations
Finucane and Pickney[10]	UK	UKAEA Systems Reliability Service	General
Nash and Young[15]	UK	UKAEA Systems Reliability Service	General
Budnick[11]	US	Collected from several sprinkler systems	General
		in one complex over 66 months	
Ronty and Keski-Rahkonen[18]	Finland	Finnish nuclear plant	Buildings in Finland
		electronic maintenance reports,	(emphasis on nuclear)
		non-nuclear building inspectionn statistics	(emphasis on nuclear)
Hauptmanns et al[17]	Germany	OREDA, IAUT-AC report	General
Gravestock[12]	New Zealand	New Zealand fire protection	fire safety systems
		industry surveys	fire safety systems
Moinuddin et al[20]	Australia	Historical data from 23 Australian *	Australian high-rise
		high-rise office buildings aged 4 to 36 years*	office buildings
SINTEF[21]		Offshore oil and gas installation	Oil and gas
		(10 - 43 pieces of equipment from 1 - 9 installations)	installations
Brammer[22]	Australia and		water supplies
	New Zealand		

Table 3.1: Studies providing data on sprinkler system component reliability.

Description	Source	Unit	Minimum	Mean	Maximum
Removal	Watanabe[19]	per demand		3.0×10^{-6}	
Deformation	Watanabe[19]	per demand		4.61×10^{-4}	
Leakage	Watanabe[19]	per demand		3.36×10^{-4}	
Obstruction (heat and water)	Watanabe[19]	per demand		1.467×10^{-3}	
Partition rearrangement	Watanabe[19]	per demand		4.89×10^{-4}	
Paint loading	Watanabe[19]	per demand		6.5×10^{-5}	
Failure	Moinuddin et al[20]	per demand		7.82×10^{-2}	
Fire detectors fail to function	Moelling et al[14]	per demand	1.99×10^{-3}	2.97×10^{-3}	4.45×10^{-3}
Fail to open	Moelling et al[14]	per demand		1.00×10^{-6}	
Failure	Ronty and Keski-Rahkonen[18]	failures/year	1.50×10^{-4}	1.70×10^{-4}	1.80×10^{-4}
Sprinkler installation	Ronty and Keski-Rahkonen[18]	failures/year	8.0×10^{-3}	1.1×10^{-2}	1.4×10^{-2}
New (fail dangerous)	Nash and Young[15]	failures/year		3.10×10^{-2}	
Old (fail dangerous)	Nash and Young[15]	failures/year		5.10×10^{-2}	
Failure to flow water	Finucane and Pickney[10]	failures/year		2.0×10^{-2}	
Water released but not in intended pattern	Finucane and Pickney[10]	failures/year		8.0×10^{-2}	

Table 3.2: Data on sprinkler head reliability.

Description	Source	Unit	Minimum	Mean	Maximum
Pipe array	Ronty and Keski-Rahkonen[18]	failures/year	2.4×10^{-6}	3.3×10^{-6}	4.3×10^{-6}
Gasket failure	Budnick[11]	failures/hour	5.00×10^{-7}	4.00×10^{-6}	1.20×10^{-5}

Table 3.3: Data on sprinkler piping reliability.

Description	Source	Unit	Minimum	Mean	Maximum
Sector control valve mishandled	Watanabe[19]	per demand		2.08×10^{-3}	
Priming tank gate valve	Watanabe[19]	per demand		2.47×10^{-3}	
Deluge fail to open	Moelling et al[14]	per demand	8.9×10^{-4}	1.9×10^{-3}	3.6×10^{-3}
Check fail to open	Moelling et al[14]	per demand	3.0×10^{-5}	1.0×10^{-4}	3.0×10^{-4}
Closed inadvertently (ICV)	Moelling et al[14]	failures per hour	6.3×10^{-7}	6.3×10^{-6}	6.3×10^{-5}
Alarm	Moinuddin et al[20]	per demand		2.0×10^{-3}	2.94×10^{-3}
Main stop	Moinuddin et al[20]	per demand		2.3×10^{-3}	3.19×10^{-3}
Zone isolation due to tenancy changes	Moinuddin et al[20]	per demand		2.2×10^{-2}	3.17×10^{-2}
Ordinary stop	Moinuddin et al[20]	per demand		6.7×10^{-4}	9.60×10^{-4}
Non-return	Moinuddin et al[20]	per demand		1.1×10^{-3}	1.76×10^{-3}
Pressure reducing	Moinuddin et al[20]	per demand		4.77×10^{-3}	1.04×10^{-2}
Wet alarm	Nash and Young[15]	failures/year		4.0×10^{-5}	
Alternative alarm	Nash and Young[15]	failures/year		8.0×10^{-5}	
Main sprinkler stop	Nash and Young[15]	failures/year		2.0×10^{-4}	
Non-return	Nash and Young[15]	failures/year		1.0×10^{-2}	
Main stop	Finucane and Pickney[10]	failures/year		2.3×10^{-3}	
Non-return	Finucane and Pickney[10]	failures/year		1.0×10^{-2}	
Main sprinkler stop	Finucane and Pickney[10]	failures/year		2.0×10^{-3}	
Wet alarm	Finucane and Pickney[10]	failures/year		4.0×10^{-4}	
Alternative alarm	Finucane and Pickney[10]	failures/year		8.0×10^{-4}	
Post indicating	Budnick[11]	failures/hour		0	
Alarm check	Budnick[11]	failures/hour		0	
Outside stem and yoke	Budnick[11]	failures/hour	7.5×10^{-8}	3.6×10^{-7}	8.7×10^{-7}
Main drain	Budnick[11]	failures/hour		0	
Inspector's test	Budnick[11]	failures/hour	2.3×10^{-6}	8.3×10^{-6}	1.8×10^{-5}
Alarm	Ronty and Keski-Rahkonen[18]	failures/year	6.5×10^{-4}	1.2×10^{-3}	2.0×10^{-3}
Deluge (Critical)	SINTEF[21]	failures/ 10^6 calendar hours	2.8	5.8	9.4
Deluge (All Modes)	SINTEF[21]	failures/ 10^6 calendar hours	12	21	31

Table 3.4: Data on sprinkler system valve reliability.

Description	Source	Unit	Minimum	Mean	Maximum
Starting device	Watanabe[19]	per demand		6.84×10^{-3}	
Fail to start	Moelling et al[14]	per demand	4.5×10^{-3}	1.4×10^{-2}	2.4×10^{-2}
Diesel	Moinuddin et al[20]	per demand		8.41×10^{-2}	1.21×10^{-1}
Electric	Moinuddin et al[20]	per demand		1.27×10^{-2}	1.90×10^{-2}
Diesel	Ronty and Keski-Rahkonen[18]	failures/year	8.7×10^{-3}	1.5×10^{-2}	2.3×10^{-2}
Electric	Ronty and Keski-Rahkonen[18]	failures/year	2.5×10^{-3}	6.2×10^{-3}	1.3×10^{-3}
Diesel (Critical)	SINTEF[21]	failures/ 10^6 calendar hours	120	210	310
Diesel (All Modes)	SINTEF[21]	failures/ 10^6 calendar hours	680	840	1000
Electric (Critical)	SINTEF[21]	failures/ 10^6 calendar hours	24	72	170
Electric (All Modes)	SINTEF[21]	failures/ 10^6 calendar hours	120	210	340

Table 3.5: Data on sprinkler system pump reliability.

Description	Source	Unit	Minimum	Mean	Maximum
Dual supplies	Brammer[22]	per demand	5.0×10^{-9}		2.4×10^{-5}
Town main	Brammer[22]	per demand	5.6×10^{-4}		1.1×10^{-2}
Pumped supply (diesel)	Brammer[22]	per demand	1.8×10^{-3}		3.8×10^{-3}
Elevated tank	Brammer[22]	per demand	1.9×10^{-4}		1.8×10^{-3}
Town main	Moinuddin et al[20]	per demand		1.87×10^{-4}	3.72×10^{-4}
Gravity tank	Moinuddin et al[20]	per demand		2.28×10^{-4}	2.28×10^{-4}
Storage tank	Moinuddin et al[20]	per demand		4.64×10^{-3}	9.34×10^{-3}
Water supply line (per m)	Moinuddin et al[20]	per demand		1.29×10^{-5}	2.18×10^{-5}
Town main	Ronty and Keski-Rahkonen[18]	failures/year	2.6×10^{-4}	1.0×10^{-3}	2.5×10^{-3}
Storage tank	Ronty and Keski-Rahkonen[18]	failures/year			6.5×10^{-3}
Pressure tank	Ronty and Keski-Rahkonen[18]	failures/year	1.0×10^{-3}	2.0×10^{-2}	9.3×10^{-2}

Table 3.6: Data on sprinkler system water supply reliability

Description	Source	Unit	Minimum	Mean	Maximum
Pressure switch	Watanabe[19]	per demand		8.99×10^{-4}	
Down time	Watanabe[19]	per demand		3.7×10^{-3}	
Incomplete protection	Watanabe[19]		1.03×10^{-4}		
Alarms fail to function	Moelling et al[14]	per demand	2.68×10^{-2}	3.62×10^{-2}	4.81×10^{-2}
Personnel fail to trip manual release	Moelling et al[14]	per demand		2.00×10^{-1}	
Back-up batteries for diesel pump	Moinuddin et al[20]	per demand		2.68×10^{-2}	4.92×10^{-2}
Mains power in building	Moinuddin et al[20]	per demand		1.61×10^{-4}	3.11×10^{-4}
Building power generator	Moinuddin et al[20]	per demand		5.24×10^{-3}	1.25×10^{-2}
Pressure switch	Moinuddin et al[20]	per demand		7.82×10^{-3}	1.17×10^{-2}
Direct brigade alarm	Moinuddin et al[20]	per demand		5.27×10^{-3}	9.57×10^{-3}
Jacking pump	Moinuddin et al[20]	per demand		9.85×10^{-3}	1.55×10^{-2}
Back-up batteries for brigade alarm	Moinuddin et al[20]	per demand		2.57×10^{-3}	6.71×10^{-3}
Alarm motor and gong	Nash and Young[15]	failures/year		1.6×10^{-2}	
Accelerator	Nash and Young[15]	failures/year		7.9×10^{-3}	
Alarm motor and gong	Finucane and Pickney[10]	failures/year		1.6×10^{-2}	
Accelerator	Finucane and Pickney[10]	failures/year		8.0×10^{-3}	
Flow alarm	Budnick[11]	failures/hour	5.80×10^{-6}	1.50×10^{-5}	2.70×10^{-5}
Motor gong	Budnick[11]	failures/hour	4.10×10^{-5}	2.50×10^{-5}	1.30×10^{-5}
Fire department connection (FDC)	Budnick[11]	failures/hour		0	

Table 3.7: Miscellaneous sprinkler system component data.

Fault/Issue	Office	Apartment	All building types
Inadequate supply	1.97%	2.38%	1.70%
Signalling fault	1.32%	2.38%	1.08%
Fire service inlet	0.66%	0.00%	1.01%
Flow switch	0.00%	0.00%	0.23%
Floor isolation	0.00%	0.00%	0.08%
Street valve	3.95%	0.00%	0.62%
Pump performance	2.63%	0.00%	1.47%
Pump start	3.29%	4.76%	1.24%
Hydraulic gong	0.00%	0.00%	0.15%
Anti-Interference gear	2.63%	0.00%	0.85%
Isolated	0.66%	0.00%	0.23%
Pressure switch	0.00%	4.76%	0.15%
Unprotected areas	1.97%	9.52%	2.48%

Table 3.8: New Zealand survey data on 1,293 sprinkler systems from 1999 to 2007[12]

Along with providing a review of other sources and recommending fire safety system component reliability distributions for risk assessment purposes, Gravestock listed sprinkler system deficiency data from inspections in New Zealand, and also collected survey data on 1,293 New Zealand sprinkler systems from 1999 to 2007, shown in Table 3.8[12]. Of the buildings included in the survey, 94% of office buildings, 76% of apartment buildings, and 89% of the total building population had sprinkler systems with minor or no defects found. The apartment buildings had a higher proportion of unprotected areas, pump start defects, and inadequate water supplies, although it should be noted that there were only 42 sprinkler systems in apartment buildings included in the survey so there is a large amount of uncertainty due to the small population of buildings. Multi-storey office and apartment buildings accounted for approximately 10% and 3% of the survey results, respectively. The category "all building types" included retail, crowd occupancy, healthcare, education, and industrial buildings in addition to office and apartment buildings.

It is difficult to directly compare component data from different sources, because of the variety of units and approaches taken, with no clear definitions of what constitutes failure for each component.

3.3 System-based studies

Total system-based studies generally use data from system operation in previous fire events from a population of buildings to estimate measures of effectiveness. The alternative approach is to obtain expert judgement through surveys or Delphi methodology. The estimates of sprinkler effectiveness from these studies are always on a per demand basis since the data comes from actual system demands.

A number of past system studies provide an estimate of sprinkler system effectiveness from fire incident data, shown in Table 3.9. The estimated effectiveness ranges from a minimum of 70.1% to a maximum of 99.5%, which corresponds to failure rates ranging from 60 failures in 200 fires to 1 failure in 200 fires.

The NFPA has published information on sprinkler system effectiveness in the United States since 1897. Estimates of satisfactory or unsatisfactory performance of sprinklers in fires are available from 1897 to 1964. It was noted that this data set did not include numerous fires extinguished by one or two sprinklers. Information on the rationale for unsatisfactory and satisfactory performance has not been identified for the NFPA data from 1897 to 1925. The NFPA has noted that reporting categories related to sprinkler performance were modified with the introduction of the National Fire Incident Reporting System (NFIRS) Version 5.0. This change was intended to improve the estimates of sprinkler reliability from the NFIRS data[24].

Knudsen and Bygbjerg[25] presented data from Danish sprinkler system inspection reports from 2001, 2007, and 2008. Deficiencies were placed into four categories:

- Category A: significant defects/deficiencies that will prevent the entire system from operating adequately (must be fixed before approval),
- Category B: defects/deficiencies that will prevent a portion of the system from operating adequately (approval will lapse if not fixed in 2 months),
- Category C: minor defects/deficiencies (must be fixed in 12 months or defect/deficiency is upgraded to category B), and
- Category BC: multiple category B or C defects/deficiencies that cumulatively are expected to equate a category A defect/deficiency.

On average, Knudsen and Bygbjerg found that 2% of inspected Danish sprinkler systems had sufficient problems to not be approved, while 40% of the inspected systems had zero defects or deficiencies identified.

There are also studies that provide information on sprinkler system effectiveness in terms of effects on the consequences from fire, such as fatalities, injuries, or amount of building floor area consumed by fire. These studies are discussed in a later section.

3.3.1 Definition of sprinkler system effectiveness

The definition of what constitutes an effective sprinkler system operation in a fire event is not consistent between studies. Marryatt defines "satisfactory" sprinkler operation as limiting the damage to the building and contents to 20% of the total value involved. He defines "controlled" fires as *"those which are extinguished by the sprinkler system by the time the fire brigade arrives, or which would be extinguished eventually without supplementary action by fire brigades or others."* This definition is slightly misleading as all fires will eventually extinguish once they have exhausted all available fuel supply. Hall Jr.[26] states that sprinkler effectiveness should be measured relative to the design objectives of the system, in most cases limiting fire spread to the room of origin.

Source	Country	Data Collected From Years	Building Population/Location	Number of Events	Nominal Reported Effectiveness
Tryon and McKinnon[27]	US	1897-1924	United States	32778	95.8%
Tryon and McKinnon[27]	US	1925-1964	United States	75290	96.2%
Hall Jr.[28]	US	1999-2002	NFIRS 5.0 data	Not Reported	89%
Hall Jr.[29]	US	2002-2004	NFIRS 5.0 data	Not Reported	90%
Hall Jr.[26]	US	2003-2007	NFIRS 5.0 data	44310	91%
Hall Jr.[30]	US	2006-2010	NFIRS 5.0 data	47520	88%
US Department of Energy[31]	US	1955-2003	US DOE facilities	251	98.8%
Miller[32]	US	1970-1972	FM insured properties	1355	85%
Powers[33]	US	1969-1978	City of New York	5709	97.0%
Taylor[34]	US	1982-1986	US general office buildings	6400 per year$*$	81.3%
Linder[35]	US	1988-1993	Industrial Risk Insurers	3446	94.9%
Baldwin and North[36]	UK	1967-1968	UK fire brigade data	619	94%
Marryatt[37]	Aus/NZ	1886-1986	Australia/New Zealand	9022	99.5%
Frank et al[38]	NZ	2001-2010	New Zealand	1171	86%
Juneja[39]	Canada	1995-2002	Ontario Fire Marshal data	2536	70.1%

Table 3.9: System-based sprinkler effectiveness studies which provide a direct estimate of sprinkler system effectiveness from past fires in sprinklered buildings.
$*$ Estimated

3.3.2 Reporting of fires that do not activate sprinklers

A major source of discrepancy when comparing sprinkler effectiveness values between studies is how fires where the sprinkler system is not activated is handled. A sprinkler system may not activate (ie. one or more sprinkler heads operating) in a fire for one of the following reasons:

1. the heat released by the fire was insufficient to activate the sprinkler system (whether or not the sprinkler system was present in the area of origin), or
2. the fire was large enough to activate a sprinkler system but a partial sprinkler system was installed and was not present in the area of fire origin, or
3. the fire was large enough to activate the sprinkler system and one or more sprinklers were present but failed to operate.

At one end of the spectrum, Marryatt[37] does not include any fires that did not operate a sprinkler, for any of the three reasons listed above. Sprinklers were reported activated in nearly all of the 49 fires that Marryatt considered the sprinkler system operation to be unsatisfactory, with the possible exception of one incident where the sprinkler system (and building) was completely destroyed in an explosion - in which case water from the broken supply piping still extinguished the fire. This is one factor that likely contributes to high reported values of effectiveness, such as the 99.5% reported by Marryatt.

At the other end, Juneja[39] includes in the operational failures all fires where a sprinkler system was installed in the building, including cases where the fire was too small to operate the system and where the fire is remote from the sprinkler system. This contributes to the low sprinkler effectiveness of 70.1% reported by Juneja, relative to the other studies.

3.3.3 Reasons for sprinkler systems to fail to operate

Table 3.10 lists the reported reasons why sprinkler systems failed to operate in the studies where this information was available. For studies that combined failures with ineffective operation, the reported percentage has been normalised to the total number of failures for comparison. The most frequent reason for sprinkler system failure, ranging from 33% to 100% of the reported failures, is that the system was shut off. Inappropriate systems, lack of maintenance, and manual intervention are reported at similar frequencies from 5% to 33%. Damaged components and frozen systems provide the minority of failures, generally near 2% with one outlier in Power's study [33] damaged components comprised 2 out of 6 failures, which is likely a reflection of the small sample size of failures.

3.3.4 Reasons for ineffective sprinkler system operation

Table 3.11 lists the reported reasons why sprinkler systems that operated were ineffective, normalised to the total number of ineffective operations. The most common reason for sprinkler systems to operate ineffectively was that the water did not reach the fire, ranging from 19% to 55% of the reported cases. An inappropriate system for the fire was the second most commonly reported reason, followed by not enough water released. These reasons are inter-related, and could have different root causes. For example, a partial coverage system may result in any of these outcomes. A change in occupancy or hazard could also result in all three outcomes: for example, a change in fuel package configuration could result in a portion of the fire being shielded, or a system designed for a light commercial occupancy could be insufficient if the use of the building is changed to storage of high-hazard materials.

Hall Jr. [26] noted that NFPA estimates of effectiveness *"exclude partial systems as identified by reason for failure and ineffectiveness equal to equipment not in area of fire"*. This approach is not likely taken in the other studies reviewed.

Source	Years	Types of Systems	Number of fires	Percent effective	System shut off	Inappropriate system	Lack of maintenance	Manual intervention	Damaged component	System frozen
Tryon and McKinnon [27]	1925-1964	Not specified	75290	96.2%	63%	15%	15%		3%	2%
Hall Jr. [28]	1999-2002	All sprinklers	Not reported	89.3%	65%	5%	11%	16%	3%	
Hall Jr. [29]	2002-2004	All sprinklers	Not reported	90%	66%	10%	10%	20%	2%	
Hall Jr. [26]	2003-2007	All sprinklers	44310	91%	53%	20%	15%	9%	2%	
Hall Jr. [30]	2006-2010	All sprinklers	47520	88%	63%	5%	6%	18%	8%	
US Department of Energy [31]	1955-2003	Water-based	251	98.8%	33%	33%			33%	
Powers [33]	1969-1978	High-rise office buildings	254	98.8%	100%					
Powers [33]	1969-1978	High-rise buildings (excl. office)	1394	98.4%	100%					
Powers [33]	1969-1978	Low rise buildings	4061	95.8%	85%	12%	3%			
Marryatt [37]	1886-1986	All sprinklers	9022	99.5%	100%					
			Mean	94.7%	73%	14%	10%	15%	9%	2%
			St. dev.	4.4%	23%	10%	5%	4%	12%	N/A

Table 3.10: Reported reasons for sprinkler systems to fail to operate.

Source	Years	Types of Systems	Water did not reach fire	Inappropriate system for fire	Not enough water released	Manual intervention	Damaged component	Lack of maintenance	Exposure fire	Faulty building construction	Miscellaneous	Unknown
Tryon and McKinnon [27]	1925-1964	Not specified	19%	35%	21%		4%		4%	13%	4%	
Hall Jr. [28]	1999-2002	All sprinklers	55%	7%	31%	2%	5%					
Hall Jr. [29]	2002-2004	All sprinklers	41%	14%	29%	6%	4%	6%				
Hall Jr. [26]	2003-2007	All sprinklers	43%	12%	31%	5%	4%	4%				
[30]	2006-2010	All sprinklers	53%	3%	18%	9%	9%	8%				
US Department of Energy [31]	1955-2003	Water-based			None reported							
Powers [33]	1969-1978	High-rise office buildings			None reported							
Powers [33]	1969-1978	High-rise buildings (excl. office)		100%								
Powers [33]	1969-1978	Low rise buildings		39%					12%	15%	18%	16%
Marryatt [37]	1886-1986	All sprinklers	26%	29%	2%	9%			13%			21%
		Mean	39%	20%	32%	6%	5%	6%	10%	14%	11%	19%
		St. dev.	14%	14%	30%	3%	2%	2%	5%	1%	10%	3%

Table 3.11: Reported reasons for sprinkler systems to operate ineffectively.

3.3.5 Number of sprinklers activated

Due to the physical evidence available, the number of sprinklers activated is a relatively simple parameter to quantify objectively. However, it is not generally clear how the number of sprinklers activated relates to the effectiveness of the system. PD7974-7:2003[40] discusses this issue, noting that some studies consider system operations with up to 200 sprinklers operating effective, and recommends four activated sprinklers as a consistent cut-off for effective operation, stating *"no more than four heads operating is the fire size typically used in a fire engineering study"*. The number of sprinklers activated was reported in a number of the sources that included fire incident data. The available information is summarised in Figure 3.2, which includes all of the data from the available studies. A boxplot of the accumulated percentage of fires where the number of sprinklers or less activated is shown in Figure 3.3. The boxplot represents the minimum and maximum percentage of sprinklers reported activated with the first and third quartile as the box limits and the median as the horizontal line in the box. To make the figure easier to read the number of sprinklers activated is limited to ten. The trend for more activated sprinklers can be inferred from Figure 3.2. The studies range from 71% to 96% at the PD7974-7:2003 recommended effective cut off point of four sprinklers.

Figure 3.4 plots the reported sprinkler effectiveness percentage versus the percent of fires reported with four or less sprinklers activated. Four sprinklers activated was used as the cut-off to compare to the PD7974-7:2003 recommendation. Most studies report a higher frequency of effective sprinkler operation compared with the frequency of fires where four or less sprinklers were reported activated, with the exception of the NFPA 2003-2007 study. This may be a reflection of the changing occupancies protected by sprinklers, as residential sprinkler systems are designed to support the operation of less sprinklers and more residential buildings are being equipped with sprinkler systems[26].

To extend the concept put forth in PD7974-7:2003 of using the number of sprinklers activated as a measure of sprinkler system effectiveness, a comparison was made between the cumulative number of sprinklers reported activated required to reach the effectiveness value quoted each study, where the information was available. This concept can be most readily explained by an example. NFPA data from 1925-1964[27] reported "satisfactory" sprinkler operation in 96% of fires, but only 71% of total fires with sprinklers had four or less sprinklers reported activated.

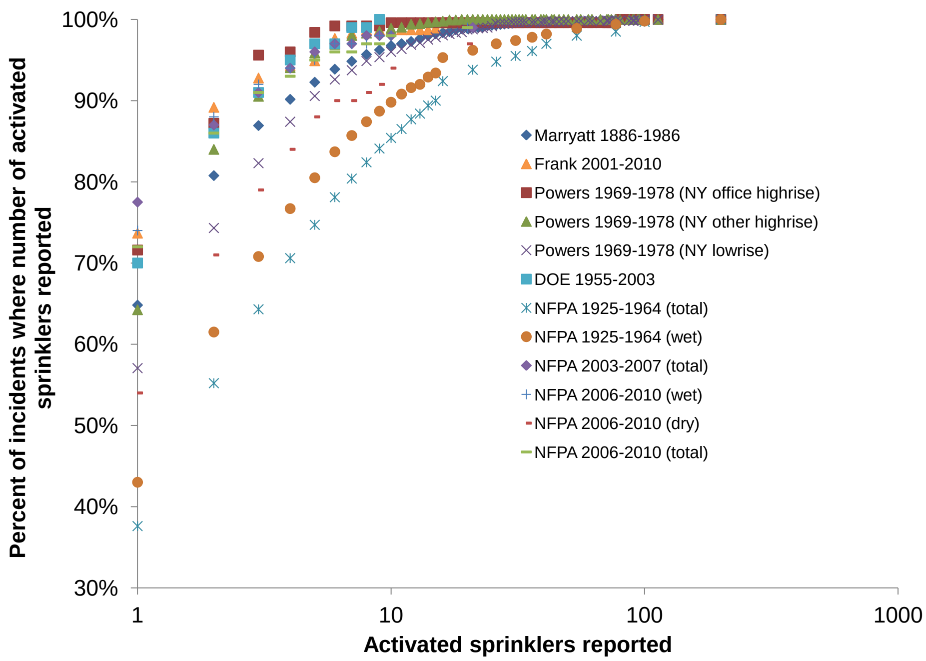

Figure 3.2: The cumulative percentage of incidents where the number of sprinklers activated were reported.

Thus, using the PD7974-7:2003 criterion of using four or less sprinklers as a benchmark for effective sprinkler system operation, the effectiveness from the 1925-1964 NFPA data would be only 71%, compared to the reported 96%. In order to include the 96% of fires where sprinklers activated and operation was reported to be satisfactory, fires with up to 36-40 sprinklers activated would need to be included.Figure 3.5 shows the relationship between the frequency of effective sprinkler operation and the cumulative number of sprinklers reported activated where the frequency equals the effective sprinkler operation frequency. In general, studies reporting a higher frequency of effective sprinkler operation required a larger number of activated sprinklers to achieve the stated effectiveness. This is potentially a reflection of the subjective criteria used to define effective sprinkler operation: studies that report high sprinkler effectiveness may have more inclusive criteria for defining effective sprinkler operation.

Typically sprinkler system water supplies are hydraulically designed to support a number of sprinklers or sprinklered area which is a function of the expected

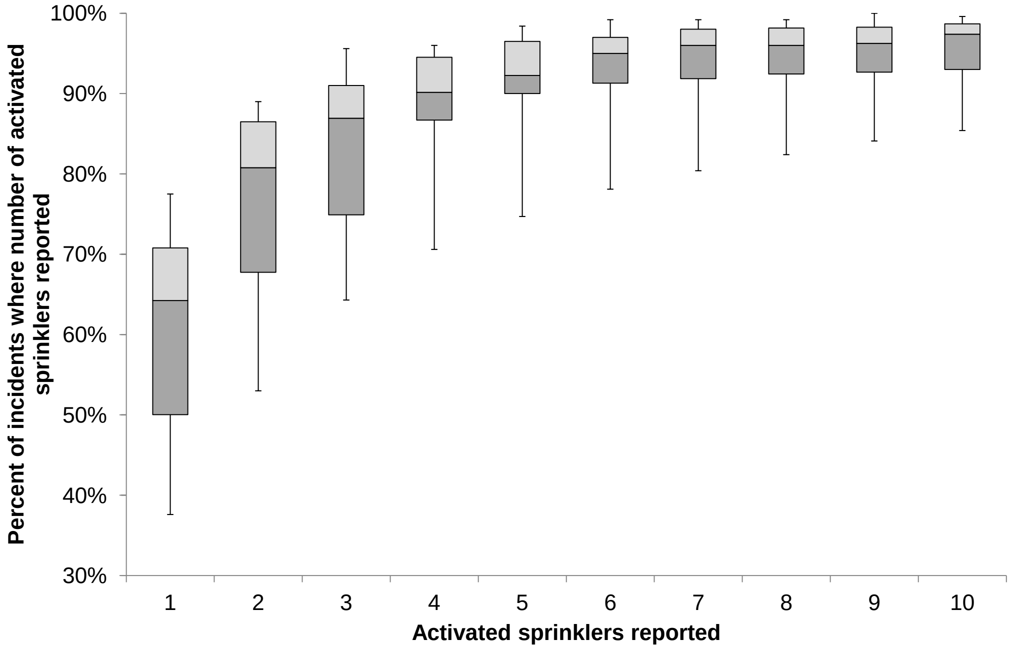

Figure 3.3: Boxplot of cumulative percentage of incidents where the number of sprinklers activated were reported (up to 10 sprinklers activated.)

Hazard	Number of fires reported	Design number of sprinklers	Design number of sprinklers exceeded	Controlled by sprinklers
Extra low hazard	30	4	23%	90%
Ordinary hazard 1	8	6	17%	88%
Ordinary hazard 2	91	12	9%	93%
Ordinary hazard 3	476	18	6%	95%
Extra high hazard	14	29	3%	79%

Table 3.12: Percentage of fires where the design number of sprinklers was exceeded and where the fire was controlled by sprinklers, from 1967-1968 UK data reported by [36].

fire hazard[23,27]. Baldwin discusses the number of instances where the design number of sprinklers were exceeded for fires in the UK from 1967-1968[36]. A table of the results from this study is shown in Table 3.12

3.3.6 Estimates of reduction in fatalities and property damage

Several system-based studies estimate the effect of sprinklers on general life safety and property protection objectives such as the number of fatalities or amount of

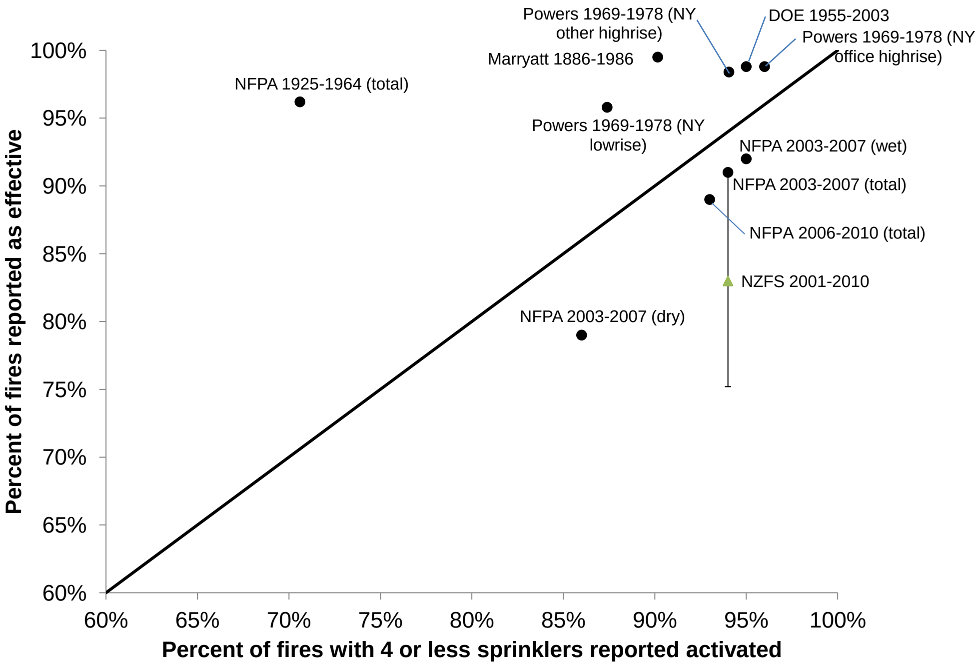

Figure 3.4: Reported effective sprinkler operation and the frequency of fires reported where four or less sprinklers operated. Wet and dry represent wet and dry pipe sprinkler systems, respectively. The uncertainty in the data from[38] is shown by the error bars.

property damage reported in fire incident data. Marryatt's study included eleven fires where fatalities occurred with an operating sprinkler system, only one of which occurred in a fire where the performance of the sprinkler system was considered ineffective, where an explosion occurred and broke the supply main to the system[37]. Of the fires with fatalities in sprinklered buildings, eight were a result of an explosion or flash fire and the remaining three were victims who were intimate with the point of ignition.

Thomas[3] estimated effects of fire safety systems on four objectives including the reduction in fire spread, civilian fatalities, and firefighter losses in fires where various combinations of detectors, sprinklers, and protected construction were present, from historical US NFIRS data. The effects of the systems were compared to a "Base Case" where none of the systems were present. Effectiveness of sprinkler systems was found to vary between -2.46 for the fire spread objective (reported average es-

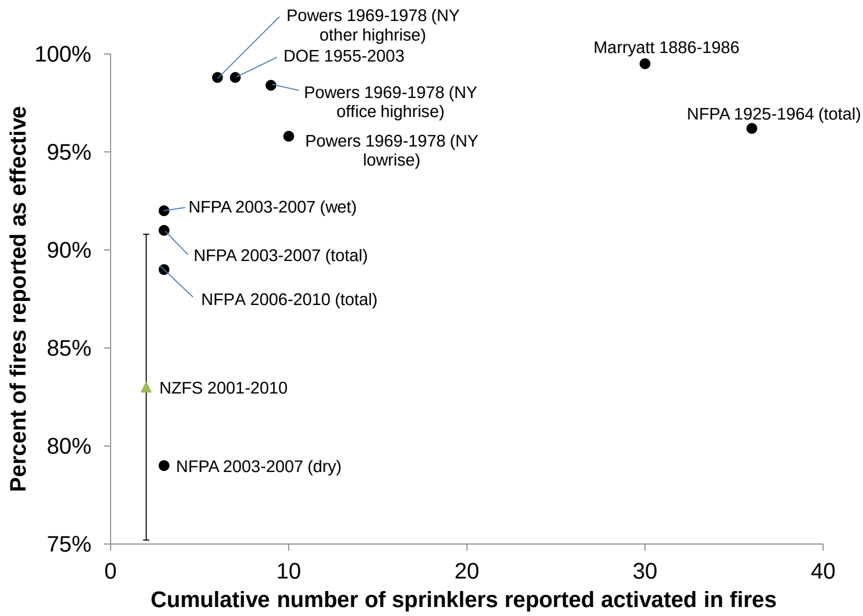

Figure 3.5: Reported effective sprinkler operation and the cumulative number of sprinklers reported operating at an equivalent frequency to the reported effective sprinkler operation frequency. Wet and dry represent wet and dry pipe sprinkler systems, respectively. The uncertainty in the data from[38] is shown by the error bars.

timated monetary loss was approximately 2.5 times higher when sprinklers were present compared to the base case)for Storage occupancy buildings and 1.00 for civilian fatalities in Hotels and Motels (reported civilian fatalities were reduced to zero). Negative effectiveness values were also calculated for detectors and protected construction. He concluded that sprinklers were generally better than detectors and fire-rated construction combined, while there was a measurable but sometimes small advantage with all three measures compared with instances where sprinklers were the only system installed.

Thomas also separated NFIRS data for the four objectives mentioned by occupancy, including Public Assembly, Institutional, Apartments, Hotels and Motels, Offices, Manufacturing, Educational, one and two Family Dwellings, Rooming and Boarding, Dormitories, Retail, and Storage. For sprinklers, he found negative effectiveness (measures of the four objectives were worse when sprinklers were present compared to the base case) for civilian injuries in the Public Assembly, Offices, Manufacturing, Educational, Retail, and Storage occupancies; for firefighter injuries in the Storage occupancy; civilian fatalities in the Educational occupancy; and fire spread (measured by average monetary loss) in the Storage occupancy.

Thomas indicated that there may be other factors that influence the apparent effectiveness of the systems considered in his study. For example, he noted that while civilian injuries increased in several occupancies where sprinklers were present, it was impossible to evaluate the severity of the injuries from the reported data, so it was possible that while more injuries occurred when sprinklers were present in some occupancies, many of them may have been less severe. A potential explanation of the increased fire losses noted in Storage occupancy buildings offered by Thomas was that storage buildings with sprinklers may be on average much larger and have much more value associated with the building and contents, although he conceded that this possibility would require more data to verify.

Melinek[41] estimated the number of casualities in the UK if all fires occurred in sprinklered buildings, by relating the number of fatalities to the extent of fire spread in sprinklered and non-sprinklered buildings. It was estimated that the number of fatalities would be reduced by approximately 50%. Melinek also looked at the effect of sprinklers on reducing the area affected by fire, and found that sprinklers had little effect on fires reaching a size of 3 m^2, but reduced the probability of a fire reaching 100 m^2 or greater area by 80% when they worked effectively[42]. Melinek also discussed the potential that less fires may be reported to the fire service in sprinklered buildings. Based on UK data from 1966 to 1972, it was noted that only 17% of calls to the fire service from sprinklered buildings were automatic. By assuming that the number of fire starts in industrial buildings was proportional to the product of the number of buildings and the square root of the mean building area, Melinek estimated that the fire services responded to 55% of the fires in sprinklered buildings that would be expected if the buildings were not sprinklered.

NFPA data from 2003-2007 indicated that sprinklers increased the probability that flame damage was confined to the room of origin to 95% compared with 74% for fires in buildings with no sprinkler systems. The fatality rate was 83% lower in fires in properties protected by sprinkler systems, and total property damage was reduced by 40%-70% depending on occupancy[26]. The 2010 NFPA report also indicates that the *"NFPA has no record of a fire killing three or more people in a completely sprinklered building where the system was properly operating."* Twenty-five fires are listed where three or more people have been killed in fully sprinklered properties in the US since 1970. Twenty-two involved an explosion or flash fire and three were a result of firefighting activities.

3.4 Uncertainty in estimates of sprinkler system effectiveness

The range in both sprinkler component and system data collected in this chapter shows that there is uncertainty in estimating the effectiveness of sprinkler systems for risk-informed fire safety design. Three studies have included suggested distributions and methodology for including uncertainty in sprinkler system estimates.

Bukowski et al[6] compiled histograms of system effectiveness estimates from a number of studies. Caution was given against using single values for estimating the effectiveness of fire protection systems. Ranges of 88% to 98% for commercial systems and 94% to 98% for general systems were given by Bukowski.

Siu and Apostolakis[43] discussed the uncertainty involved in using expert judgement to estimate the reliability (or "demand availability" as termed in the original paper) of sprinkler systems in specific installations. A Bayesian approach was used to combine small sets of directly relevant incident data with partially relevant data from general populations of sprinklered fire incident data and system test data. Their work also provides techniques to account for and assess an expert's expertise in supplying data estimates. Data from 16 nuclear facility sprinklered fires was supplemented with "expert" data represented by Industrial Risk Insurers' sprinkler test data and NFPA sprinklered fire data with associated bias factors to estimate a posterior distribution for the reliability of a sprinkler system in a nuclear facility. The distribution Sui and Apostolakis arrived at for the base case sprinkler reliability in a nuclear facility had a mean reliability of 89% with a standard deviation of 6%.

Gravestock[12] recommended uncertainty distributions for sprinkler system component reliability estimates, as well as upper and lower bounds for system effectiveness. Gravestock noted that where information on distribution shape is unknown, but upper and lower bounds are known, a uniform distribution may be appropriate which assigns equal probability to all potential values within the bounds. If the upper and lower bounds are known and a value of maximum probability is known, a triangular or PERT distribution may be more appropriate. Gravestock recommended using a mean effectiveness of 90% for sprinkler systems in apartments and 95% for sprinkler systems in offices, with lower bounds ranging from 46% to 89% and upper bounds ranging from 97% to 99%.

In Chapter 4, the uncertainty in sprinkler effectiveness reported in New Zealand Fire Service fire incident reports from 2001 to 2010 is estimated. Probability distributions for sprinkler effectiveness from the reported data were developed using a decision tree approach.

3.5 Comparing component-based studies with system-based studies

While it is difficult to directly compare component-based studies and system-based studies, a number of observations can be made. First, the majority of failures reported in real fires are due to the system being shut off, an inappropriate system, and manual intervention and these failures are not generally captured in component-based studies, although some component-based studies attempt to. One example is the study by Moelling et al, which does discuss the probability of inadvertently closed valves[14]. Second, component-based studies may capture some reasons for ineffective operation, such as not enough water released in the case of a pump not operating, but again, the majority of reasons such as partial systems, inappropriate systems, or manual intervention are not captured in component-based approaches. However, component-based studies may capture failures for lack of maintenance or damaged components. While data for the exact components used may not be available, the use of a component-based approach allows reliability estimates for the specific set of component types used in an individual sprinkler system to be combined.

In most cases, studies presenting sprinkler system component data do not elaborate on the failure modes considered. Other than a few exceptions, component reliability is generally considered to be binary, either the component operates successfully or it fails completely. Correlations between the failure of components are not considered: for example, it is possible that multiple components may fail simultaneously or in close succession, particularly if poor maintenance practices are employed. Thus estimating overall system effectiveness from component-based data is difficult.

System-based studies, by their nature, provide the best average estimates of overall sprinkler system effectiveness. However, since fires are relatively rare events, system-based studies do not provide detailed information on specific types of sprinkler systems or specific sprinkler system configurations. Fires occur in all ages of buildings, so even new fire incident data includes old sprinkler system designs. In general, the specifications or standard that the incident sprinkler systems were designed to are not available. Maintenance, inspection, and testing data is also not included, so it is difficult to estimate the effects of these aspects on system effectiveness. Changes to the building use and hazard between the time of design and the incident are not likely to be recorded. Thus it is difficult to estimate how system improvements such as upgraded water supplies or piping networks, or improved inspection, maintenance, and testing practices, will improve system effectiveness from system-based studies.

Given the limited information available, the recommended approach to estimate effectiveness for a specific system is to take a distribution of effectiveness for general sprinkler systems from system-based studies, and to modify using data from component-based studies. The relative contribution of each component to system effectiveness can be estimated from the component data, and the effect of making a change to the sprinkler system (such as improving the water supply or improving inspection) should then be considered on a comparative basis with the base system rather than on an absolute basis.

3.6 Conclusions and Recommendations

Given how common sprinklers are and how long they have been in use in building fire protection it may be surprising how little is known regarding their effectiveness. This chapter has summarised available sprinkler system component data and effectiveness estimates for sprinkler systems from fire incident data studies, with discussion of the relative merits of each approach and the uncertainty involved.

A number of recommendations can be made for estimating the effectiveness of a sprinkler system for performance-based design. Due to the majority of sprinkler failures being related to human errors, component-based study data should not be used exclusively without comparison to system-based study data. Adjusting sprinkler system effectiveness due to a system modification such as additional water supplies or valve monitoring should be based on an estimate of the number of failures observed in real fire incidents that would be prevented by the proposed change. The modified effectiveness for the system change can be supported by component-based data.

The limited data available and subjective nature of fire incident data precludes the use of a single point value for sprinkler effectiveness in performance-based fire safety design. A range of values with associated probabilities should be used to appropriately represent the uncertainty in estimating sprinkler effectiveness from available data. The sensitivity of the proposed fire safety design to the uncertainty in the sprinkler system effectiveness should be investigated.

For an estimate of the effectiveness of general fire sprinkler systems, the available data indicates that a range of sprinkler system effectiveness from a minimum of 70% to a maximum of 99.5% may be possible, or ineffective sprinkler operation in a range from three in ten fires to one in 200. The highest probability of sprinkler system effectiveness appears to be between 90% and 95% or between one in ten and one in 20 ineffective sprinkler operations in fires. For most design purposes, both the extreme upper and lower limits of reported effectiveness are not likely applicable due to the definitions used for effective sprinkler operation in these studies discussed previously. Data pertaining to the applicable jurisdiction should also be considered with greater weight than data from jurisdictions due to varying practices of design, installation, maintenance, and inspection. If using a probabilistic model, a uniform, triangular or PERT distribution shape may be the most appropriate to use with a peak between 90% and 95% and upper and lower bounds estimated from the applicable studies for the situation being considered.

For future data collection, the definition of effective sprinkler system operation should be made clear when it is being reported as such. Discrete system functions (eg. notification and suppression) should be clearly separated in the data fields. Less subjective measures such as the number of sprinklers activated as a percentage of the number of sprinklers for which the system was hydraulically designed to supply and the number of sprinklers activated inside and outside the compartment of origin would be useful. Integration with inspection, testing, and maintenance data would be useful to provide information on how these factors influence effectiveness. Chapter 4 discusses specific recommendations for improving data collection in New Zealand, some of which may be suitable in other jurisdictions.

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CHAPTER 4

UNCERTAINTY IN ESTIMATING THE FIRE CONTROL EFFECTIVENESS OF SPRINKLERS FROM NEW ZEALAND FIRE INCIDENT REPORTS

4.1 Fire incident data collection in New Zealand

The NZFS is a national fire service and has used a web-based incident data reporting system since 2000, which is a integrated with the overall station management system (SMS). An incident number and report are automatically generated for all incidents that the NZFS is dispatched to, and includes the radio communications between the dispatcher and the NZFS operational staff. A task in the web-based time management system is then created for the officer-in-charge or a delegated person to complete the data fields in the incident report. Most data fields have discrete entries, but there is also a field that allows additional written explanatory comments. There are many advantages to the NZFS incident reporting system; for instance, since there is one system in use across the country, all incident reports are completed in the same format. NZFS members are all trained in one system for filling out incident reports. The system is not voluntary and contains all incidents that the NZFS responds to. However, this does not guarantee the accuracy of the information reported, or that all data fields pertinent to a particular incident will be completed. Also, data field completion is not guaranteed during times of industrial action by the firefighters' union, since a form of action that has been used is refusal to complete incident reports[1]. In the incident reports reviewed, a fire in a sprinklered building was reported in a NZFS incident report on average every three days, however during the 2009 industrial action there was a span of 81 days with no fires in sprinklered buildings reported.

A staff of twenty Fire Safety Officers are available to assist in fire investigations, as well as specialist Fire Research and Investigation and Fire Engineering groups. National Commander's Instruction (NCI) number 56 requires that specialist fire investigators are involved in *"fires in buildings where built-in fire safety features have failed, or not performed to known or expected standards."* Furthermore, NCI 56 requires a full investigation report from the specialist fire investigator for every incident *"involving the failure of fire protection systems or fire safety features to contain or control a fire"*[2]. SMS and full investigation reports are required within 14 days and one month of the incident, respectively. The data considered in this report was obtained from the SMS reports, some of which appeared to have additional comments added by Fire Safety Officers or other specialist fire investigation staff.

4.2 Review of NZFS data from fires in sprinklered buildings

The population of fires that this study considers includes all of the fires where sprinkler systems were reported by the NZFS during the period from 2001-2010, excluding chimney fires and fires in residential buildings with less than 10 household units. There were a total of 7,283 fires that reported some type of detection system, of which 1,171 fires reported a sprinkler system present, including 25 fires where residential sprinklers were reported and 33 fires where domestic sprinklers were reported. The performance of the sprinkler system was reported as "operated and effective" in 613 fires, "operated and ineffective" in 27 fires, and "too small to activate system" in 191 fires. Of the remainder, it was reported that the system operated in 167 fires, did not operate in 124 fires, and operation was not reported in 49 fires. A further breakdown can be seen in Figure 4.1.

Table 4.1 categorises the reported fires by occupancy. The occupancy reported most frequently was industrial and manufacturing, followed by hospitals or care facilities, and shops.

An estimate of sprinkler system effectiveness in fires that the NZFS responded to can be calculated by treating this data objectively "as reported". Removing the 191 fires reporting that the fire was too small to activate the sprinkler system and the

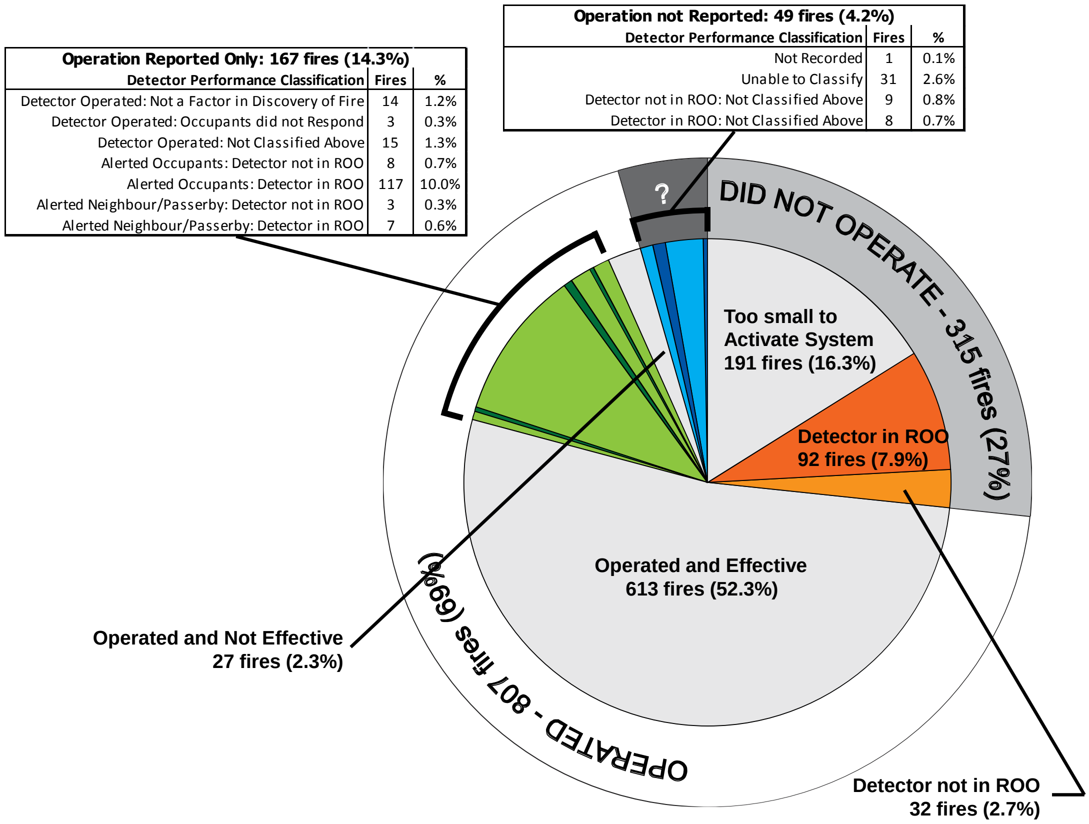

Figure 4.1: Sprinkler system performance from 2001-2010 NZFS fire incident data as reported (ROO - Room of origin).

49 fires where the operational status of the sprinkler system was not reported ("not recorded", "unable to classify", or "detector... not classified above") and dividing the 613 fires where the sprinkler system was reported as "operating and effective" by the remaining fires, an effectiveness of 66% is calculated. This value is much lower than the commonly quoted 99.5% effectiveness value reported by Marryatt for Australia and New Zealand[3], values from other historical studies reviewed in the literature[4], and also lower than recent data from the NFPA in the US, which indicates an overall effectiveness of 91%[5].

The following reported performance categories:

- Did not operate - detector in room of origin
- Did not operate - detector not in room of origin

Occupancy	Number of Fires
Industrial, Manufacturing	360
Hospital, Hospice, Rest home, Rehabilitation centre	166
Shop, Shopping mall, Supermarket, Service station, Car yard, Other sales use	123
Office, Bank, Embassy, Fire/Ambulance/Police station	77
Flat, Apartment, Home unit	73
Prison, Correctional institution	51
Restaurant, Pub, Tavern	51
Boarding/Half-way house, Dormitory, Rooming, Home stay, Backpacker	37
Hotel, Motel, Lodge, Timeshare	36
Storage, Warehousing	28
Commercial - not classified above	23
Recreational use, Theatre, Indoor sports, Pool, Park, Zoo, Aquarium	21
University, Polytech, Teachers college, Other post-secondary	20
School: Pre-school through to Secondary/High	18
Educational, Health, Institutional - not classified above	13
Library, Museum, Art gallery, Court etc	12
Service/Repair use, Dry cleaner, Laundromat, Mechanical workshop	12
Airport	10
Recreational, Assembly - not classified above	6
Residential - not classified above	4
Rubbish tip, Transfer station, Hazardous waste disposal	4
Unable to classify	4
Doctors/Dentists emergency clinic, Medical centre	3
Vacant building, Section	3
Church, Cemetery, Religious use	2
Community hall	2
Farming, Horticulture, Agricultural use	2
Power station	2
Sports club, Health club	2
Sportsfield, Stadium	2
Construction, Renovation, Demolition site	1
Defence, Military use	1
Stormwater, Harbour, Lake, River, Beach, Waterfront area	1
Telephone exchange, Communications use, Control room, Data processing	1
Total	**1171**

Table 4.1: Number of fires reported in sprinklered buildings from 2001-2010 NZFS data, by occupancy. Residential buildings with less than 10 household units excluded.

indicated that the sprinkler system did not operate, with a separate data field ("fire detector failure") recording the reason why the system did not operate. A total of 124 fires or approximately 10% of the total were reported in these categories. In the majority of cases, the fire detector failure field reported "unable to classify", "unknown", or other categories that were not a clear indication of a failure, as shown in Table 4.2.

Also, the categories:

- Alerted neighbour/passerby - detector in room of origin

	Detector in Room of Origin	Detector not in Room of Origin	Total
Defective detector	1	1	2
Defective discharge head or outlet	1		1
Improper installation/Placement of detector	4	1	5
Inadequate maintenance	5		5
No detectors in room or space of fire origin	14	9	23
Not enough agent discharged to control fire	3	1	4
Power supply failed	2		2
System shut down	4		4
Unable to classify	43	6	49
Unknown	15		15
Detector not in room of origin		14	14
Total	**92**	**32**	**124**

Table 4.2: Reasons reported for sprinkler systems not operating from 2001-2010 NZFS data.

- Alerted neighbour/passerby - detector not in room of origin
- Alerted occupants - detector in room of origin
- Alerted occupants - detector not in room of origin
- Detector operated - not classified above
- Detector operated - but occupants failed to respond
- Detector operated - but was not a factor in the

indicated operation but did not provide indication of fire control or suppression effectiveness. A total of 167 fires were reported in these categories. Including these fires and the fires where the sprinkler system was reported operating and effective or ineffective, there were 807 fires where the sprinkler system was reported as operating (Figure 4.1).

4.2.1 Number of activated sprinklers reported

Of the 807 fire reports where it was indicated that a sprinkler system was present and did operate, 474 also reported how many sprinklers had operated. Figure 4.2 compares the number of sprinklers reported activated between the 2001-2010 NZFS data, 2003-2007 NFPA data[5], 1925-1964 NFPA data[6], and 1886-1986 Australian and New Zealand data from Marryatt's study[3].

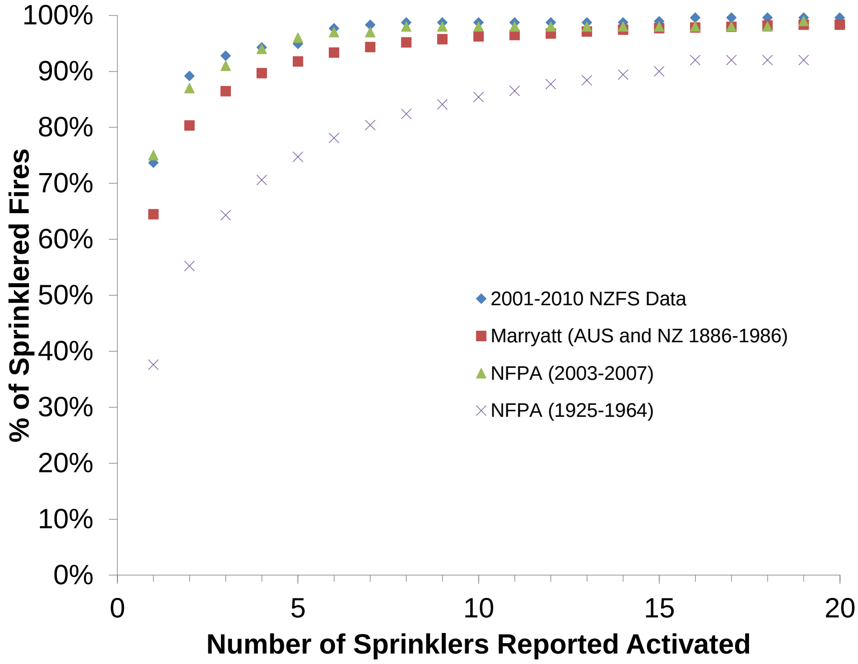

Figure 4.2: Number of activated sprinklers reported. The 2001-2010 NZFS and 2003-2007 NFPA data are comparable.

It appears that the number of sprinklers activated in fires is trending downward in both the US and New Zealand, which could reflect an improvement in sprinkler system effectiveness. Other factors that could affect the number of sprinklers activated in fires are changes in the occupancies and fuel package configurations that sprinkler systems are installed to protect, such as an increase in residential occupancy buildings being protected by sprinklers.

4.2.2 Multiple fires in a single sprinklered building

Four sprinklered fires were recorded in a restaurant in Auckland, where the sprinkler was activated in a duct. A fifth suspicious fire originated beside the building in some stacked furniture, eventually breaking the exterior windows and causing two interior sprinklers to activate.

A wood processing facility on the South Island experienced multiple fires in storage silos. The sprinkler system was originally installed to wet the shavings, ie.

not for fire protection. It was subsequently altered but was never built to any fire sprinkler code.

4.3 Injuries and fatalities in sprinklered buildings in New Zealand

4.3.1 Injuries

There were 15 instances identified in the data set where moderate injuries were reported with no fatalities. In two cases, the fire was reported as too small to activate the sprinkler system. The sprinkler system responded in the other 13 of the cases, and was effective in eight of those, although in one case the injuries were exacerbated by the sprinkler system activating. A female staff member at a rest home was removing a burning pot from an electric range when the sprinkler activated. The water discharged from the sprinkler caused the hot contents of the pot to splash onto the victim. In three incidents the sprinkler effectiveness could not be determined from the incident report.

4.3.2 Fatalities

The following information on fatalities in sprinklered buildings in New Zealand was obtained from Chris Mak of Aon, and verified by accessing the NZFS incident reports for each. There were eight known fire deaths in sprinklered buildings in New Zealand since 1996. Four of the fatalities happened in care facilities or rest homes, two in a prison, one in a "halfway house," and one in a multi storey hotel. All of the casualties were intimate with the fire. Only one of the fatalities was included in the SMS data set analysed because the incidents were either before the period of time considered or in structures not included in the data set.

One of the rest home fires was ruled suicide by fire by the coroner. The 35 year old male casualty doused himself with petrol and ignited it directly below a sprinkler head. Reports indicate that the fire was extinguished by the sprinkler but not before the casualty sustained burns which would eventually be fatal. Two of the fatalities were a result of careless disposal of smoking materials igniting flammable clothing or furniture and giving the casualties fatal burns. It was reported that the sprinkler systems activated in both cases. Both victims were male, aged 76 and 86 years old. The fourth fatality was a 101-year male who received fatal burns when an electric heater ignited clothing and the fire spread to a chair and bed. The sprinkler operated and extinguished the fire. The fire engineering unit of the NZFS conducted an in-depth investigation into the fire and sprinkler system [7] and concluded that while there were compliance issues with the sprinkler installation, they did not adversely influence the fire outcome.

Both of the fatalities in prisons involved fires in cells set by inmates. In one case, an inmate doused another with petrol and ignited it, inflicting fatal burns on the victim. While the fire service was contacted, the responding appliance was stood down before it reached the incident so no information on the operation of the sprinkler is available. In the second incident, the inmate disabled the sprinkler by wrapping blanket strips around it, and then ignited bedding in his cell. He suffered fatal burns as a result - the report also lists 12 additional people with injuries from smoke inhalation.

The fatality that occured in a halfway house was a result of the occupant setting fire to the room contents. It has been reported that the sprinkler did not operate, but that it had been part of a voluntary replacement program in the early 2000s due to a known problem and had not been replaced.

The eighth fatality occured at a fancy dress christmas party in a hotel. A male and female were in a toilet cubicle on the fifth floor and a third individual ignited the fancy dress costume of the male in the cubicle, resulting in burns to 95% of his body [8]. The female also received significant burns. The sprinkler system operated and extinguished the fire.

4.3.3 Sources of uncertainty

There are many sources of uncertainty when estimating sprinkler system effectiveness for risk-informed performance-based fire safety design from fire incident reports, yet many sprinkler system studies based on the data, including those previously cited in this report by Marryatt and the NFPA, do not discuss uncertainty in their reported numbers.

The task of determining which factors influenced fire development in a fire investigation can range from trivial to nearly impossible. Fire investigation can be a subjective process subject to large uncertainty. An example is given by Carman where 53 fire investigators with a variety of knowledge and experience were asked to examine two burn cells and determine which quadrant of the room the fire started in. For both cells, the success rate was 3 out of the 53 students, or 5.7%[9].

Resources for investigating each fire are limited, particularly if the consequences are not severe. However in terms of statistics, small fires are as important as large fires. It is unlikely that fire investigation reports are 100% reliable in terms of providing accurate information on system effectiveness for performance-based engineering design. The question that arises is then how much value can we get from fire investigation reports for estimating fire risk? The following section discusses a number of factors noted in the reviewed NZFS incident reports that contribute to the uncertainty in estimating sprinkler system effectiveness from them.

Firstly, the occupancy and type of sprinkler system reported were not coherent in several instances where domestic or residential sprinklers were reported. Of the 33 fires where domestic sprinklers were reported, six were reported as being in a type of residential occupancy. The remainder were reported in eight rest homes or institutions, four industrial properties, four shops, two schools or day cares, and several other commercial occupancies. By definition, domestic sprinkler systems should not have been included in the population of fires considered by this study, as residential buildings with less than ten household units were excluded. Of the 25 fires where residential sprinklers were reported, 18 were reported in residential or other sleeping occupancies, three were reported in industrial occupancies, and others were reported in a prison, a recreational facility, a police station, and a commercial property.

Secondly, the term "effective" is subjective and there does not appear to be any consistent definition available for NZFS staff for evaluating sprinkler system effectiveness. For the purposes of this study, "effective" operation is defined to be the product of reliability (did the sprinkler operate when a sufficient fire event occurred) and efficacy (did the sprinkler system suppress or control the fire as expected), as defined in Chapter 1. Previous studies have used a variety of definitions. For example, Hall discusses this issue and states that effectiveness should be measured relative to the design objectives of the system, which in most cases is to confine the fire to the room of origin[5]. The British Standards Institution published document 7974-7:2003 which provides guidance on probabilistic risk assessment for fire safety design of buildings recommends using 4 activated sprinklers as a cutoff for effective sprinkler system operation[10]. Marryatt uses 20% destruction of the protected property as the cutoff for effective operation in his study[3]. As discussed in Chapter 1, the proposed New Zealand C/VM2 Verification Method for Fire Safety Design assumes the sprinkler system will be able to control the heat release rate once the first sprinkler activates[11]. However, it is difficult or impossible to determine whether the sprinkler system met this criteria after a real fire.

It was apparent that many of the performance data field categories discussed above did not provide clear information on whether the sprinkler system had indeed activated, if it would have been expected to (for example, that the fire was large enough to activate it), or if it was effective at suppressing or controlling the fire. By reviewing other related data fields, an attempt was made to reclassify the ambiguous reports of sprinkler effectiveness. Other data fields that were reviewed included the arrival condition (condition of the fire when the first NZFS appliance arrived), equipment used by the NZFS for the incident, fire spread, and comments. The message logs between dispatch and the operational staff were also reviewed. Some reports had comments that explicitly stated that the fire was too small, or reported arrival conditions of "out on arrival", no fire or smoke, or smoke only, and reported only that the sprinkler system had not activated.

Evidence used for effective sprinkler operation included evidence that the sprinkler system had operated and:

- Fire spread limited to room of origin
- Situation report in message log stating that the fire was suppressed with a hose reel or extinguisher (thus indicating a small fire)
- 4 sprinklers or less reported as activated
- Comments suggesting that the sprinkler operation was effective at suppressing the fire
- Arrival condition indicating small fire, "out on arrival", no fire or smoke, or smoke only

Some instances where the operation of the sprinkler system was reported as ineffective had notes in the comments section indicating the reason for reporting the system as ineffective was the water flow gong not sounding or the alarm not activating. In some cases, other information in the reports such as the written comment section indicated that the sprinkler system did suppress the fire.

Of the 807 fires where sprinkler operation was reported, 333 or 41% did not report the number of sprinklers operating. The number of sprinklers operating is one indication of whether the sprinkler system was likely to have been overwhelmed or not, and as previously discussed is the metric proposed in PD7974-7:2003 for evaluating effectiveness. However, sprinkler systems are not all hydraulically designed to supply the same number of sprinklers. For example, the New Zealand sprinkler standard NZS4541:2007 allows the water supply to provide for only the 4 most hydraulically remote sprinklers where residential sprinklers are installed, but requires 18 sprinklers to be supplied for a system installed to protect a Group III high ordinary hazard, such as general warehousing and storage[12]. Using a cutoff of 4 activated sprinklers to indicate effective sprinkler operation does not seem to be an appropriate measure of effectiveness for a sprinkler system designed to supply 18 sprinklers. However, the NZFS fire incident data does not provide a sufficient level of information to determine the hydraulic design information.

4.3.4 Reclassification

The 367 fire reports where sprinkler system performance was potentially ambiguous were manually reviewed. The sprinkler system performance was subjectively reclassified for reliability and effectiveness where inconsistencies were noted or where the reported sprinkler system performance code was not informative for suppression effectiveness, where supported by additional information from the incident reports. Otherwise, the reliability or effectiveness was classified as "uncertain" if there was minimal information supporting the outcome or "likely" if there were multiple positive indicators for the outcome. Table 4.3 lists the results of the reclassification procedure.

The reclassified estimates of sprinkler effectiveness were then used to produce generalised reliability, efficacy, and overall effectiveness uncertainty distribution estimates, based on the inconsistances observed within the reports.

Reclassification	Number of Fires	Percent of Total
Effective	669	57%
Likely effective	3	0%
Effectiveness uncertain	55	5%
Likely ineffective	3	0%
Ineffective	26	2%
Likely operated	44	4%
Operation uncertain	21	2%
Likely did not operate	49	4%
Did not operate	12	1%
Too small	268	23%
Likely too small	6	1%
Likely not involved	3	0%
Not involved	12	1%
Total	**1171**	**100%**

Table 4.3: Results of reclassification of 2001-2010 NZFS fire incident data where sprinkler systems were reported.

4.3.4.1 Uncertainty in Type of System Present

The number of domestic and residential sprinkler systems reported was used as an evidence of the proportion of fire reports where the type of system was reported in error. Thus, the 95% confidence interval ($\pm$ two standard deviations assuming a normally distributed uncertainty) in number of fires in sprinklered buildings was estimated at 60 fires. The mean number of fires in sprinklered buildings was estimated to be the nominal number reported, or 1171 fires.

4.3.4.2 Uncertainty in Sprinkler Operation

It was uncertain whether the sprinklers had operated or not in 114 fires, based on the review of the fire incident reports. The reclassified categories that were used for this estimate are shown in Table 4.4. There were a total of 756 fires where sprinkler operation was reasonably certain (Table 4.5).

Of the nominally 396 fires where sprinkler operation was estimated to have not occurred, it was reasonably certain that in 12 instances the sprinkler system should have activated, and it was uncertain if the sprinklers should have activated in 58 fires (Table 4.6).

Reclassification	Number of Fires
Likely operated	44
Operation uncertain	21
Likely did not operate	49
Total	**114**

Table 4.4: Reported fires where sprinkler operation was uncertain.

Reclassification	Number of Fires
Effective	669
Likely effective	3
Effectiveness uncertain	55
Likely ineffective	3
Ineffective	26
Total	**756**

Table 4.5: Reported fires where sprinkler operation was reasonably certain.

Reclassification	Number of Fires
Likely did not operate	49
Likely too small	6
Likely not involved	3
Total	**58**

Table 4.6: Reported fires where the sprinklers did not appear to activate and the reason for not being activated was uncertain.

4.3.4.3 Uncertainty in effective sprinkler operation

The evidence in the reports from 669 fires was reasonably consistent with effective sprinkler operation. The number of fires where effective operation was uncertain was estimated to be 126, shown in Table 4.7.

4.3.4.4 Decision tree analysis

Estimated normal distributions for the above quantities were combined in a decision tree to estimate the sprinkler reliability, efficacy, and effectiveness in New Zealand from 2001-2010. A binomial distribution approach was also taken in parallel. The binomial probability density function is given as follows:

Reclassification	Number of Fires
Likely effective	3
Effectiveness uncertain	55
Likely ineffective	3
Likely operated	44
Operation uncertain	21
Total	**126**

Table 4.7: Reported fires where sprinkler effectiveness was uncertain.

$$\binom{n}{k} p^k (1-p)^{n-k} \tag{4.1}$$

where n is the total number of trials (for example, number of fires where a sprinkler system is present), k is the number of successes (for example, the number of fires where a sprinkler system operated), and p is the observed probability of achieving a success (for example, a sprinkler system operating). By using the binomial distribution, the probability that the observed events match the true population can be observed. The binomial distribution assumes that all events have equal probability, which is not accurate for sprinkler system activations in fires because every fire scenario and sprinkler system is different. It does provide a minimum level of uncertainty in the ability of the sample set (fires reported in sprinklered buildings) to represent the overall population (expected effectiveness of sprinklers in New Zealand).

The decision tree can be seen with normal and binomial distributions in Figures 4.3 and 4.4, respectively. The decision tree was split into four decisions relevant to determining sprinkler system effectiveness:

1. Was a sprinkler system present?
2. Did it operate in the fire?
3. Should it have operated?
4. If it operated, was it effective?

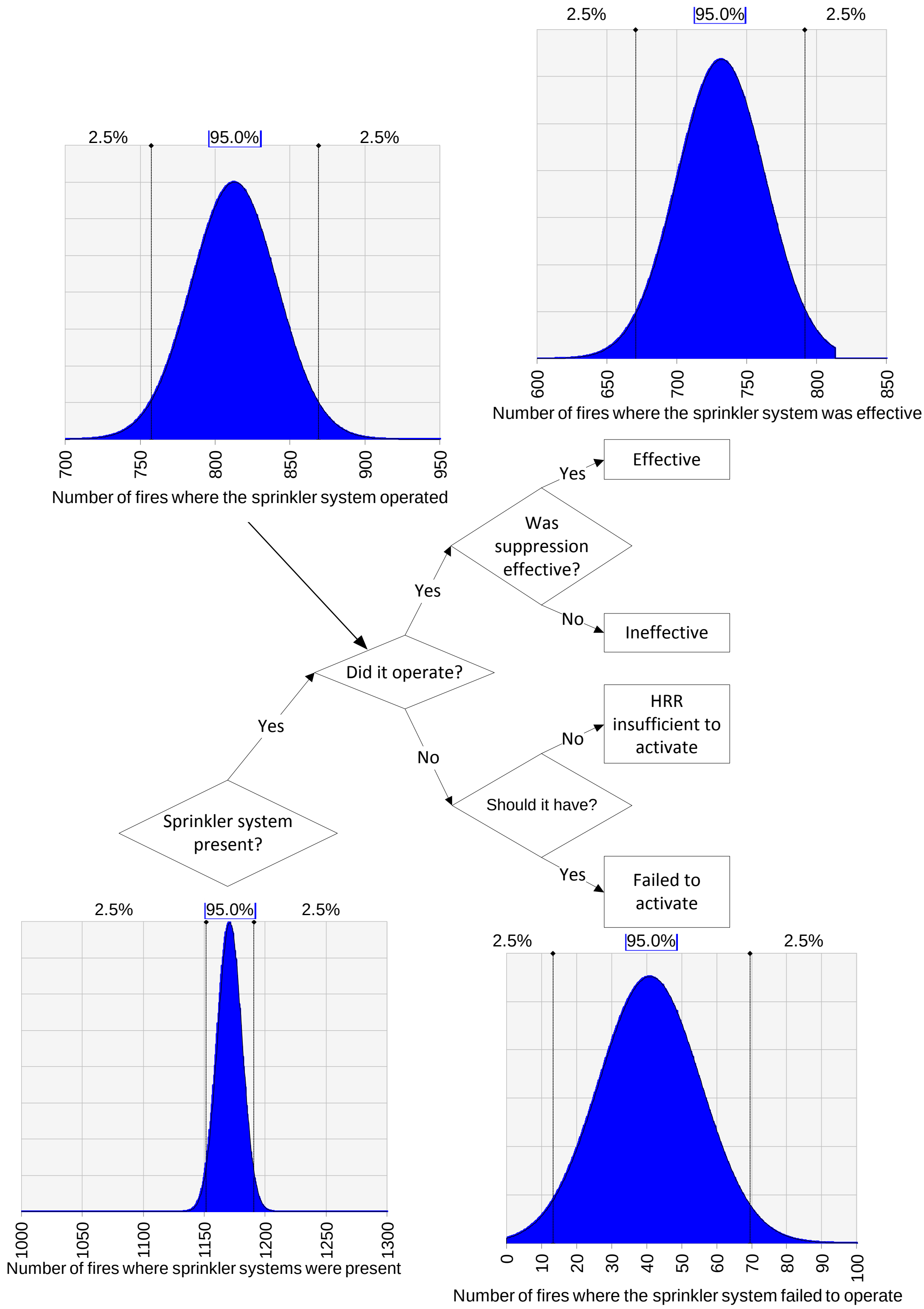

Figure 4.3: Decision tree for estimating uncertainty in sprinkler effectiveness from 2001-2010 NZFS fire incident reports. Estimated normal distributions are shown.

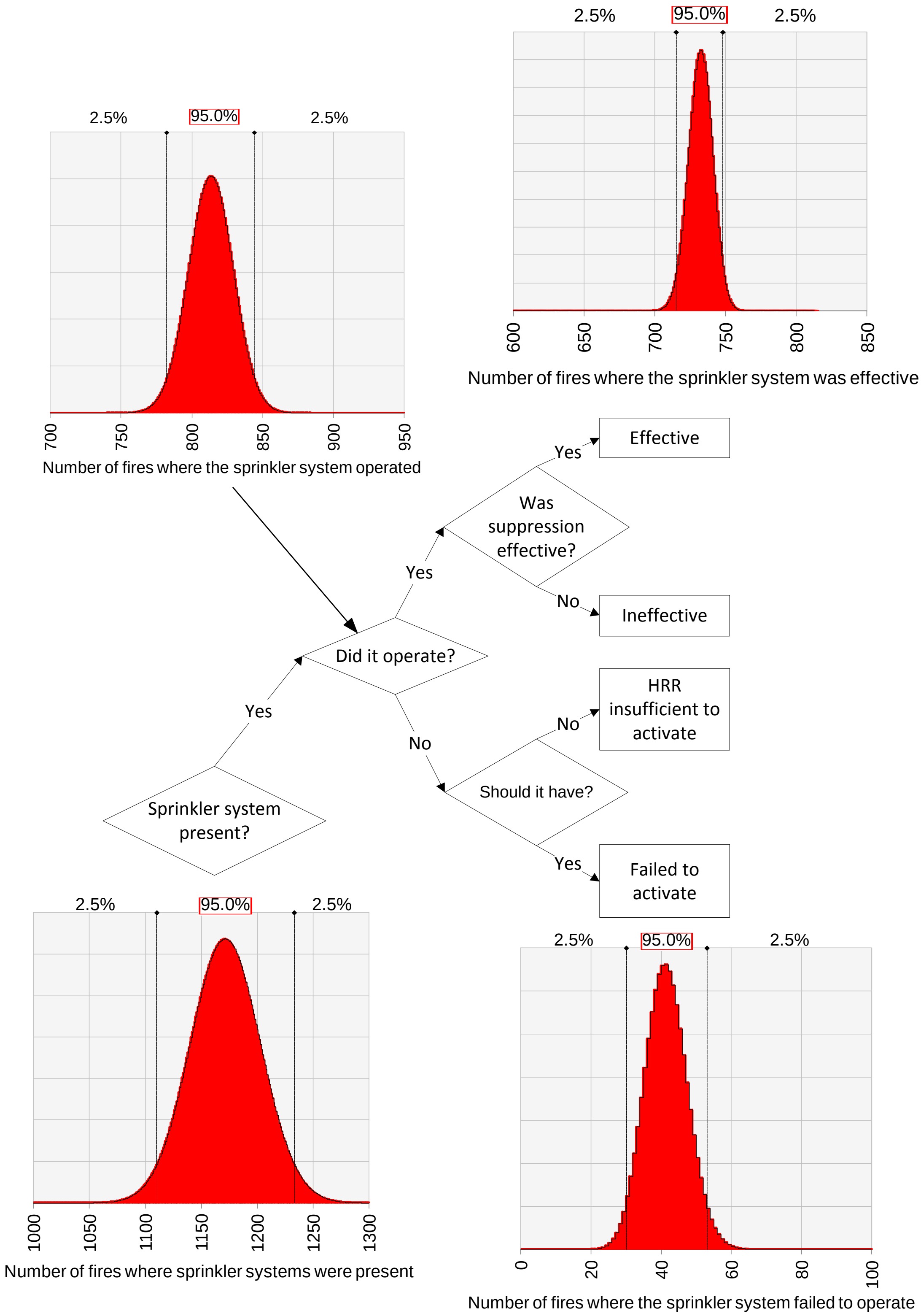

Figure 4.4: Decision tree for estimating uncertainty in sprinkler effectiveness from 2001-2010 NZFS fire incident reports. Estimated binomial distributions are shown.

Distributions were estimated for the number of fires where sprinklers were present, the sprinklers operated, and the sprinklers were effective. The number of fires where sprinklers did not operate was calculated by subtracting the number of fires with operating sprinkler systems from the total number of fires in sprinklered buildings. The number of ineffective sprinkler activations in fires was similarly calculated by subtracting the number of effective sprinkler activations from the total number of sprinkler activations.

An additional distribution was estimated for the number of fires where sprinklers did not operate but would have been expected to. The number of fires where the fire was not large enough to activate the sprinkler system was calculated by subtracting the number of fires where the sprinkler system did not operate but would have been expected to from the total number of fires where the sprinkler system did not operate. Distributions were truncated where the extent of the tails would have caused impossible outcomes: for example, more effective sprinkler activations than total activations.

4.3.4.5 Normal distribution parameter definition

For the distribution representing the number of incidents where sprinkler systems were present, the recorded number of fires (1171) was used as the mean, with the number of fires where a domestic sprinkler system was reported or a residential sprinkler system was reported in a non-residential occupancy (40 fires) used to estimate a 95% confidence interval (+/- two standard deviations).

The 95% confidence interval for sprinkler operation was estimated as the sum of fires classified as likely operated, operation uncertain, and likely did not operate (114 fires). The mean for the number of fires where the sprinkler system operated was calculated by adding fires classified as operated (756 fires) and half of the 95% confidence interval (57 fires) for a mean of 813 fires.

The effective sprinkler operation 95% confidence interval was estimated as the sum of the fires classifed as likely effective, effectiveness uncertain, likely ineffective, likely operated, and operation uncertain (126 fires). The mean was estimated to consist of the fires classified as effective (669 fires) plus half of the 95% confidence interval (63 fires) for a total of 732 fires.

The 95% confidence interval for the number of fires where the sprinkler system failed to operate when it would be expected to was estimated to be the sum of the fires classified as likely did not operate, likely too small, and likely not involved (58 fires). The mean was estimated to be the fires where the sprinkler system was classified as did not operate (12 fires) plus half of the 95% confidence interval (33 fires) or 41 fires.

4.3.4.6 Binomial distributions

Binomial distributions were defined by using the total number of fires where the outcome was possible and the mean number of outcomes calculated for the normal distributions. For example, the number of possible fires n where sprinkler systems could be present was defined as 1171 and the probability p was defined as 813/1171. The total population of fires where some type of detection system (including smoke detection and other systems) was used as the number of possible events (7283 fires) for defining the binomial distribution for sprinkler system presence.

4.3.4.7 Monte Carlo simulation

A Monte Carlo simulation of the decision tree was run with the commercial software @Risk[13] using both the normal and binomial distributions. Results for sprinkler reliability, efficacy, and effectiveness are shown in Figures 4.5, 4.6, and 4.7 respectively, with comparisons to previously mentioned sprinkler effectiveness studies.

A summary of best fit distributions to the Monte Carlo output as determined by @Risk is given in Table 4.8. The Kolmogorov-Smirnov test was used as the measure of goodness-of-fit for the fitted distributions. The mean estimate for sprinkler reliability was approximately 2% greater than the nominal value obtained by the NFPA for 2003-2007 US sprinklered-building fires. The mean efficacy estimate was lower at 90% compared to the 2003-2007 NFPA nominal value of 97%. The combined mean effectiveness estimate was 86% compared with the 2003-2007 NFPA value of 91%, and much lower than Marryatt's reported value of 99.5%. This could be a result of Marryatt's definition of effective operation and the fact that Marryatt did not include any fires in sprinklered buildings where the sprinkler system did not operate, other than cases where the sprinkler system was shut off.

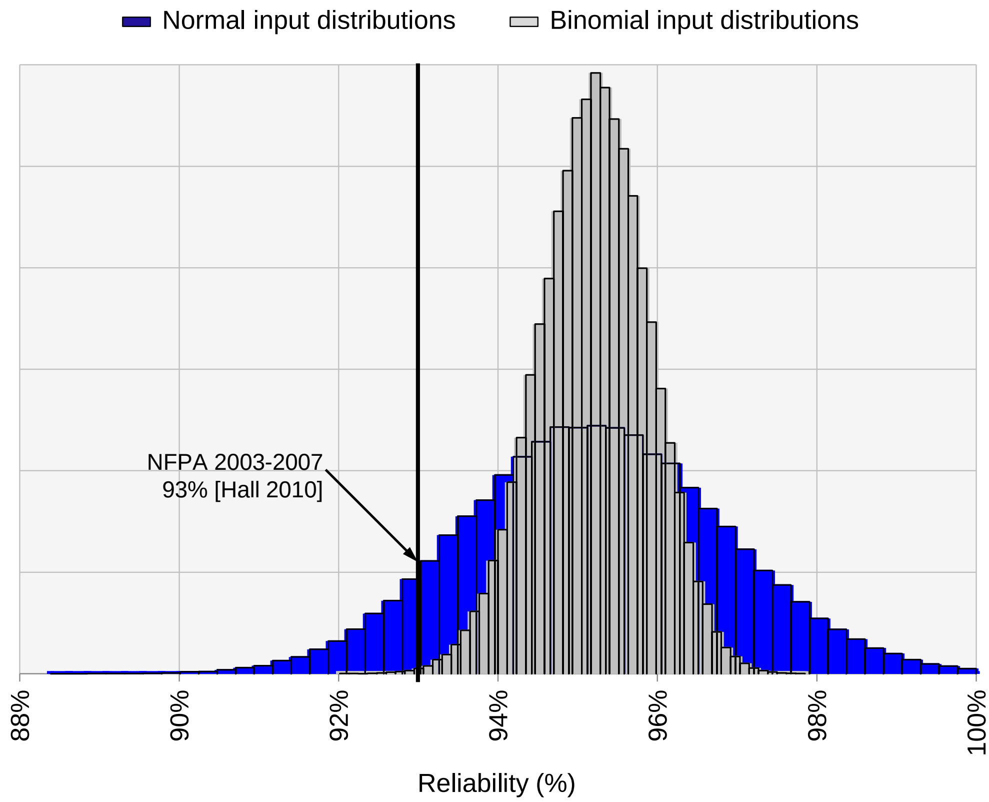

Figure 4.5: Estimated reliability uncertainty distribution, with comparison to 2003-2007 NFPA data [5].

A comparsion between the PD7974-7:2003 guidelines for sprinkler effectiveness in probabilistic risk analysis is given in Figure 4.7. The uncertainty range in sprinkler effectiveness estimated from the NZFS data was consistent with the recommended range given in PD7974-7:2003, considering that the NZFS fire incident data contained all the categories of systems for which PD7974-7:2003 gives explicit guidance.

4.3.5 Suggested improvements for data collection

4.3.5.1 Linking to other information sources

It is clear that there is uncertainty in statistics from fire incident reports in identifying the systems that were present in the building at the time of the fire and what their

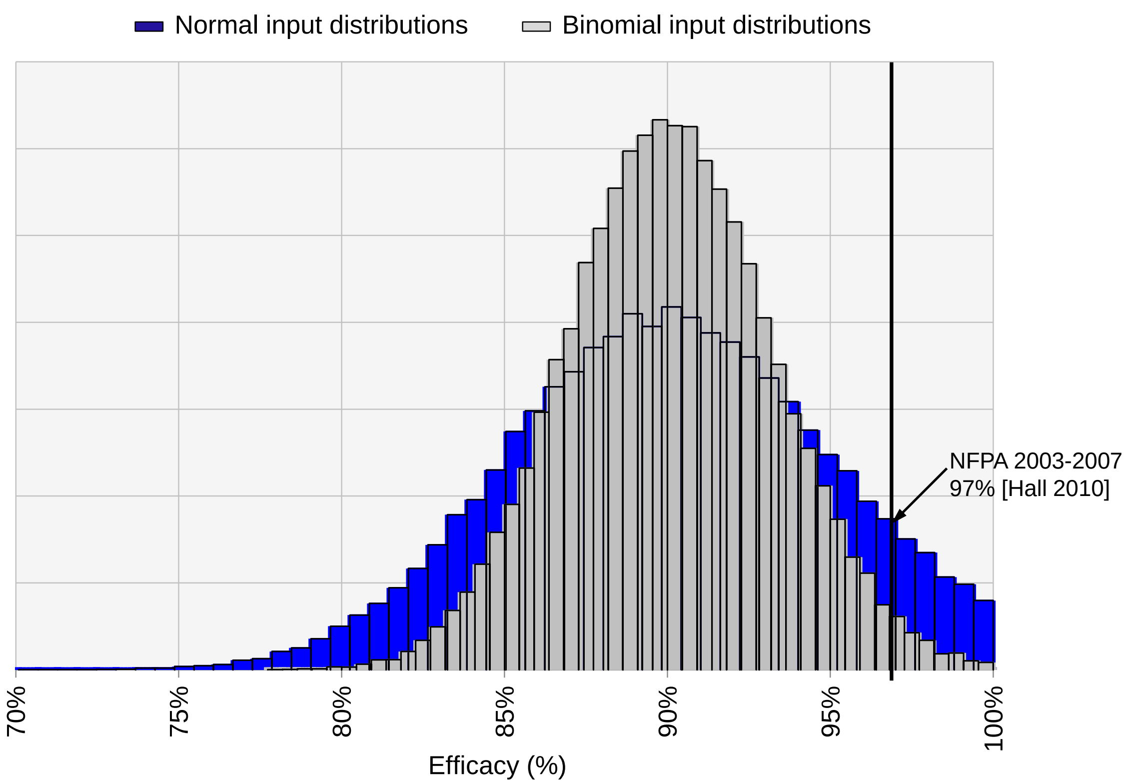

Figure 4.6: Estimated efficacy uncertainty distribution, with comparison to 2003-2007 NFPA data[5].

Input Distributions	Output	Best Fit Distributions			
		Type	Mean	St. Dev.	K-S
Normal	Reliability	Lognormal	95%	1.6%	0.003
	Efficacy	Normal	90%	4.7%	0.015
	Effectiveness	Normal	86%	4.6%	0.001
Binomial	Reliability	Normal	95%	0.7%	0.011
	Efficacy	Normal	90%	3.2%	0.004
	Effectiveness	Lognormal	86%	2.9%	0.002

Table 4.8: Table of best fit distributions for Monte Carlo decision tree simulation, with Kolmogorov-Smirnov test statistic.

pre-fire status was. Rather than relying on the fire investigator to determine this information post-fire when evidence of the systems may be partially destroyed, it is proposed that this information be provided at the design or inspection of the systems in the building and automatically populated in a fire incident report by sharing information between data sources if a fire should occur. This will reduce the work-

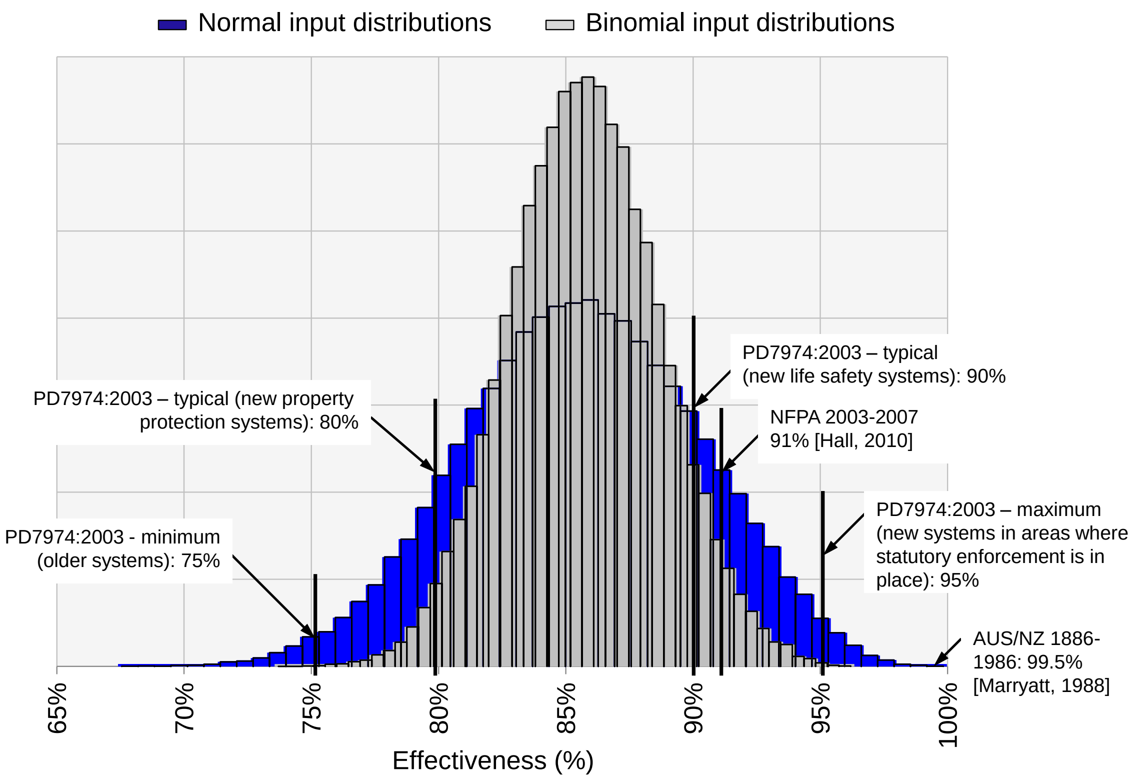

Figure 4.7: Estimated effectiveness uncertainty distribution, with comparison to 2003-2007 NFPA data[5], Pd7974:2003 guidance[10], and Marryatt's study[3].

load required of the fire investigator and reduce the uncertainty in the information. Some examples of potentially useful information for sprinkler systems that could be automatically populated in fire incident reports from design documentation:

- the standard that the system was designed to
- number of sprinklers or sprinklered area that the water supply for the system was hydraulically designed to support
- the type of water supply for the system
- if the valves were monitored or not

Some examples of potentially useful information for sprinkler systems that could be automatically populated in fire incident reports from inspection reports:

- design information for existing buildings
- any faults or issues with the system
- the date of last inspection
- a link to the previous inspection report
- the flow characteristics of the water supply at the time of inspection

In New Zealand, fire sprinkler systems that meet New Zealand standards must be approved by a Sprinkler System Certifier (SSC) and tested, inspected, and maintained by an approved contractor[12]. These organisations maintain databases on sprinkler system initial installation inspections and periodically required re-inspections, which could be a source for this information.

4.3.5.2 Changes to the data fields

The current set up of the NZFS fire incident report data fields has been shown to be ambiguous for determining sprinkler system effectiveness for risk-informed performance-based fire safety design. A single field for fire detector performance is used for all types of detectors, and no other field for sprinkler performance is available. Not only does this not allow the performance of sprinklers and other detectors to be both reported for fires in buildings that contain both, but field options for both detection and suppression performance get mixed with no way to separate effectiveness for these two distinct functions. Thus, the detection and suppression functions should be split into separate data fields for greater clarity. The NFIRS 5.0 system[14] could be used as a template.

A known problem occurs with the location of fire origin being associated with a particular room in the building when the location was in fact in a wall space, duct, or roof cavity within the structural members adjacent to the room. The sprinkler system is then presumed to have failed when the fire was in fact beyond the reach of a sprinkler system. This reflects a failure to appreciate the intention of reporting on fire protection system performance. Ideally, reporting of fire protection system performance needs to distinguish failures of design from failures to operate as intended.

Additional fields could be added that would provide less subjective information on sprinkler system effectiveness. For example:

- percent of sprinklers activated in the compartment of origin
- number of sprinklers activated outside the compartment of origin

fields would provide information on whether all of the sprinkler in the compartment where the fire was ignited were required, and if the fire was able to reach the size where sprinklers outside that compartment were activated. This would be particularly useful in evaluating the effectiveness of residential systems, as approval tests of residential systems used by FM and UL use activation of a sprinkler mounted in the doorway of the room of fire origin as a criteria of passing or failing[15].

4.3.5.3 Guidelines for assigning additional investigational resources

The observation of inconsistent data for fires in sprinklered buildings indicates that there may be a lack of expertise or other resources required for providing accurate reports on many fires. It is unlikely that the resources will be available for investigators with specialised knowledge of fire safety systems to attend every incident where the systems are present. However, by analysing the data initially collected by the incident reporter, the use of specialised investigation resources can be optimised. Potential data inconsistencies observed in the 2001-2010 NZFS data on fires in sprinklered buildings that could be flagged automatically for further review by specialised personnel include:

- sprinkler system operation reported and number of sprinklers activated not reported
- occupancy and system type incompatibility
- successful sprinkler operation and substantial suppression equipment reported used by the brigade (eg. multiple low pressure deliveries, multiple alarms)

- successful sprinkler operation and arrival conditions of large fire or totally involved
- sprinkler system reported as not effective or not operating and non-fire arrival condition (out on arrival, smoke only, no fire or smoke)
- sprinkler system reported as not operating (without reporting a fire that is too small to activate the system) and limited suppression equipment used by the brigade (eg. one hose reel only, one extinguisher)
- sprinkler system reported as effective with flame or smoke damage reported extending past room of fire origin
- sprinkler system reported as not operating (without reporting a fire that is too small to activate the system) with flame or smoke damage reported confined to room of fire origin
- operation not indicated: not reported or unable to classify

in addition to any reports of ineffective operation. An initial consultation with a specialist investigator could consist of reviewing photos or video of the fire scene and telephone interviews with the initial investigator. If the issues are not resolved in this process, a site visit by the specialist may provide more information. If the inconsistent data can not be resolved, a written note in the comment could be a required input for further explanation.

4.4 Conclusions

While a lack of data on system effectiveness has been identified as a key barrier for successful performance-based fire safety design, the usefulness of data on fires in sprinklered buildings collected by the NZFS from 2001 to 2010 appears to be limited for this purpose. A review of ambiguous reports indicates that the reliability of sprinkler systems (ability to respond to a fire event and provide water) in fires that the NZFS responded to was approximately 95% and efficacy was 90%, for a total effectiveness of 86% with a standard deviation of uncertainty of 4.6%. This can be compared with the historical study completed by Marryatt from which a sprinkler effectiveness of 99.5% is commonly cited for sprinkler systems in Australia and New Zealand [3].

The current data coding setup is not ideal for reporting the effectiveness of sprinkler systems. The categories for reporting fire detector performance do not provide sufficient capacity to report on the ability of the sprinkler system to meet its primary objectives; namely, fire control and notification. There appears to be large differences in the subjective interpretation of “effective” operation. Improvements could be made by linking the reports to design and inspection data, changing the coding scheme, and identifying instances where additional expertise may provide insight.

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CHAPTER 5

UNCERTAINTY IN CALCULATING FIRST SPRINKLER ACTIVATION

5.1 Introduction

In this chapter sources of aleatoric uncertainty are compared with the epistemic uncertainty when modelling the first sprinkler to activate with a two-zone computer fire model. Two scenarios are considered: the first models a set of experiments conducted at the University of Canterbury, and the second considers the same room geometry but as a design scenario where the item ignited is a polyurethane foam upholstered chair or sofa and where the spatial location of the fire in the room is uncertain. The relative importance of the epistemic model uncertainty is compared between scenarios. Two output parameters are considered; the time of sprinkler activation and the heat release rate (HRR) at the time of sprinkler activation. The relative sensitivity of the model to each of the uncertain parameters is discussed.

5.2 Model description

An early version of B-RISK was used for the simulations discussed in this chapter. The structure of the model can be seen in Figure 5.1.

5.2.1 Deterministic model

The BRANZFire[1] two zone model was used as the deterministic model to calculate the sprinkler activation time. Details of how BRANZFire calculates the layer properties can be found elsewhere[1,2]. In BRANZFire, plume air entrainment can either be

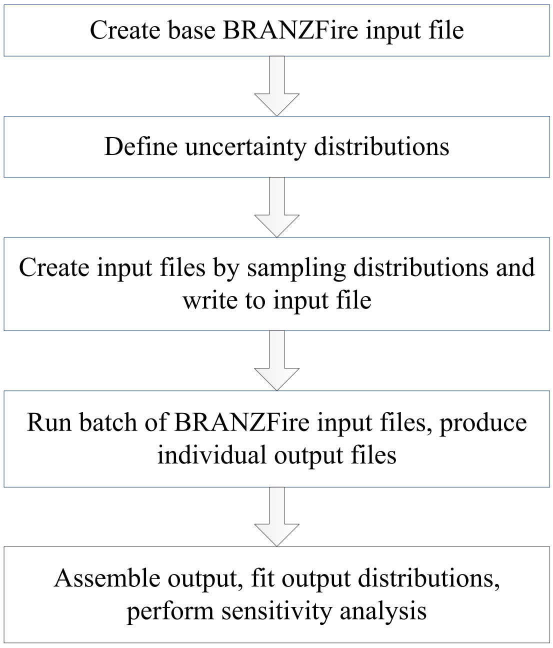


Figure 5.1: Probabilistic-deterministic model structure.

calculated with Delichatios' or McCaffrey's correlations. McCaffrey's correlations are chosen for this study because they were used in the BRANZFire verification report[3]. BRANZFire predicts the ceiling jet temperature and velocity based on either Alpert's correlations[4] or the JET model[5], which includes the effects of the upper layer under a confined ceiling. The JET model is considered here because a previous study has indicated that it provides more accurate results in small rooms when compared with Alpert's correlations[2]. The LAVENT method from NFPA 204[6] resolves the variation of the ceiling jet temperature and velocity with distance below the ceiling. The detector thermal response is modelled by Heskestad and Bill's differential equation[7]. The choices in submodels represent decision uncertainty.

5.2.2 Probabilistic model

At the time this section of the research was completed, sprinkler uncertainty capability had not been entirely implemented in B-RISK. Thus, the commercially available software program @Risk[8] was used to sample input parameter probability distributions for use in the deterministic model. The Latin Hypercube sampling approach was used to ensure that the extreme values in the distributions are sampled adequately. The sampled values are written to BRANZFire input files, which

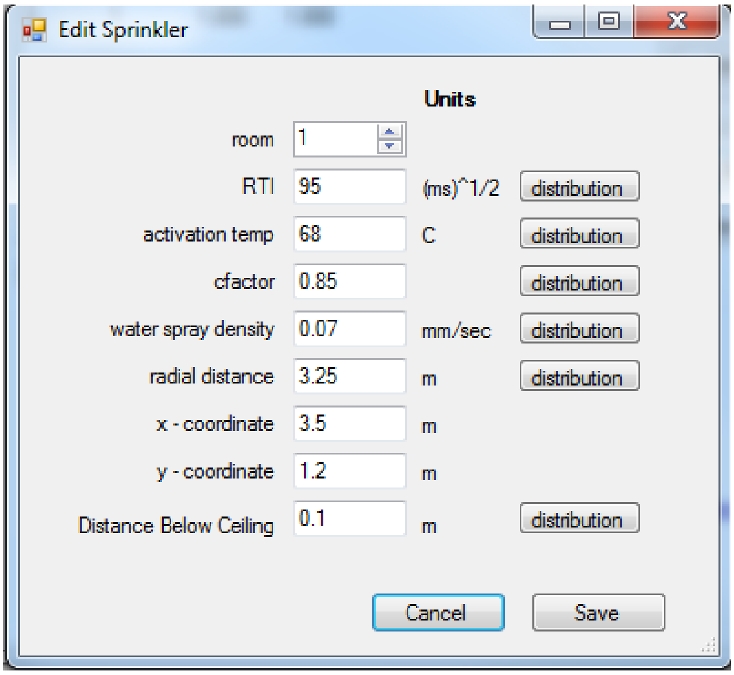


Figure 5.2: Values and distributions for sprinkler response model parameters are entered into B-RISK in the form shown here.

are then run as a batch producing individual output files. The output data is then collected for analysis in Excel. The output from 5000 iterations was compared to 1000 iterations; the mean and variance was similar for the output distributions but the distributions were smoother with 5000 iterations. The maximum standard sample mean error is 0.9% for both sprinkler activation time and HRR at the time of sprinkler activation with 5000 iterations. Pearson's correlation coefficient is used to compare sensitivity of the sprinkler activation time and HRR at the time of sprinkler activation to the sources of uncertainty, because of its ubiquity and ability to measure the degree of relation between the input and output as a standardised slope[9].

In the new B-RISK model, sprinkler response model parameter values and distributions are entered into the form shown in Figure 5.2.

5.3 Scenarios

Two separate scenarios are considered to evaluate the relative uncertainty contribution of the parameters. The first scenario is based on specific sprinkler activation tests conducted at the University of Canterbury[10]. The second scenario uses the same room geometry as the first scenario but the uncertainty in the fire parameters is expanded.

5.3.1 Scenario 1

The first scenario is based on three tests out of a series of ten where a single chair was burned in the centre of a room with the door open. The three tests are considered because they were repeat tests with the same ignition scenario, type of sprinkler, and ventilation conditions. The experimental room was 8 m long, 4 m wide, and 2.4 m high, based on the dimensions of the UL 1626 room[11]. The walls and ceiling were light timber frame with 10 mm painted gypsum plasterboard. No uncertainty is considered in the room geometry or the material properties of the room lining. Two Tyco TY3251 standard response, pendant, spray sprinklers with a nominal activation temperature of 68 ^{o}C were installed and located 2 m from the centre of the room. The sprinklers were oriented so the yoke arms were perpendicular to the radial direction of the fire. The sprinklers were pressurised with water to measure the activation time with pressure switches but no water supply was connected. A plan view of the experimental layout is shown in Figure 5.3. The chair was comprised of cushion grade non-fire retarded polyurethane foam blocks (approximately 0.56 kg each), covered with acrylic fabric and backed by 10 mm plasterboard as seen in Figure 5.4. The chair was placed on a load cell to measure the mass loss during the fire, and the heat release was calculated based on the mass loss measured by the load cell and an effective heat of combustion obtained from cone calorimeter tests. The interior temperature varied from 23 ^{o}C to 27 ^{o}C. A summary of the experimental results is shown in Table 5.1.

5.3.2 Scenario 2

The second scenario considers the same room geometry as Scenario 1, but the fire parameters have much more variability, as could be expected under real-world design conditions. The room geometry is considered to be known with no uncertainty, and the door is considered open. The location of the fire is uncertain. The fuel item is a piece of furniture with polyurethane foam cushioning, but it is uncertain if it is a single-seat chair, two-seater or three-seater sofa.

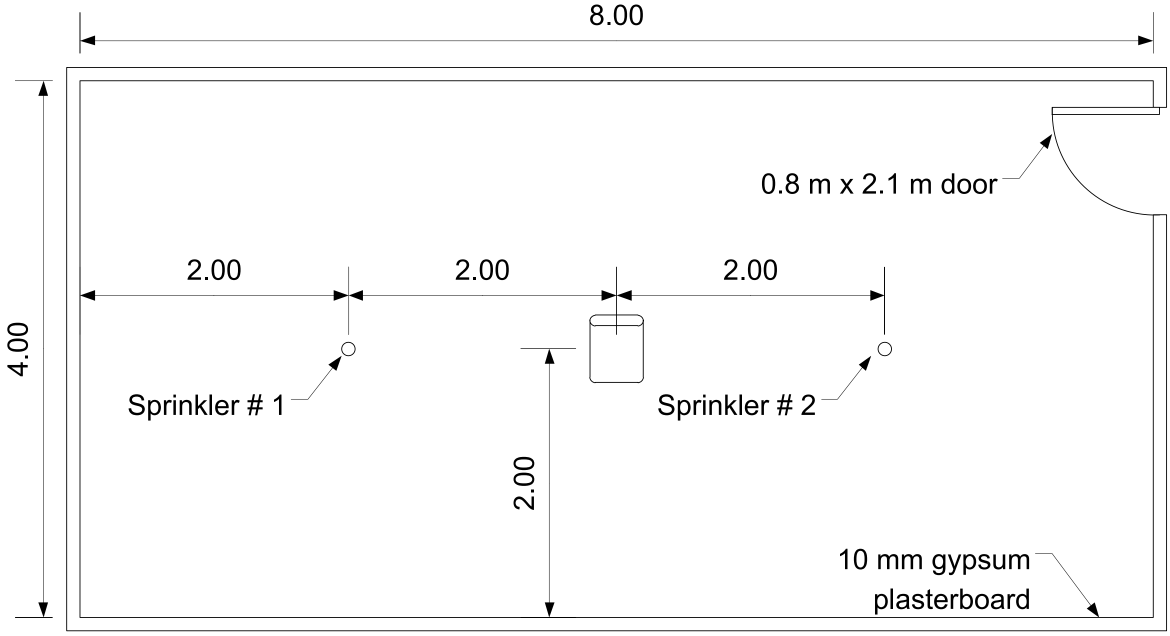


Figure 5.3: The layout of the experimental room (extracted from Bittern[10]). Dimensions in metres unless otherwise stated.

Experiment	Sprinkler	Sprinkler activation time (s)	HRR at sprinkler activation (kW)	HRR Growth rate α (kW/s^2)
4	1	226	125	0.0024
	2	226	125	0.0024
5	1	216	129	0.0028
	2	211	126	0.0028
6	1	266	116	0.0016
	2	272	125	0.0017
Mean		236	124	0.0023
Standard deviation		26	4.4	0.0005

Table 5.1: Experimental results for Scenario 1[10].

5.4 Sources of uncertainty considered

The sources of uncertainty that are quantified are summarised in Figure 5.5. The ambient temperature is modelled as a normal distribution with mean 25^{o}C and standard deviation 1^{o}C to match the range in the experiments. The maximum and minimum sampled values for all the distributions that are not truncated have been checked to make sure that no unrealistic extremely improbable values were included in individual simulations.

Figure 5.4: Upholstered chair configuration considered for Scenario 1 (extracted from Bittern[10]).

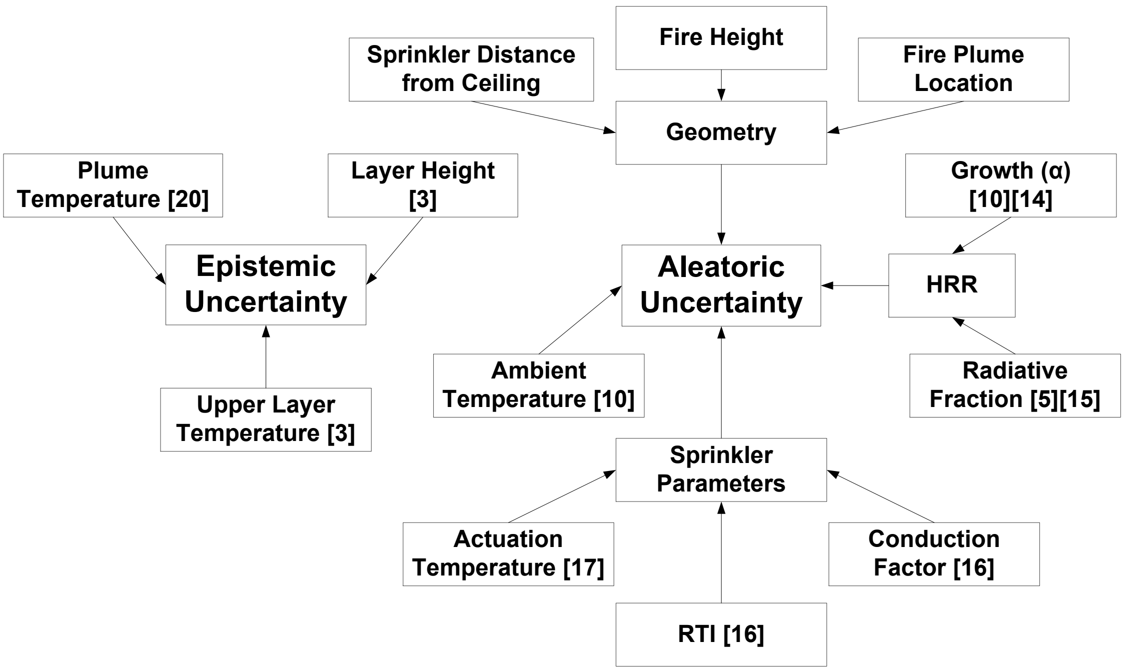


Figure 5.5: Quantified sources of uncertainty categorised as epistemic or aleatoric uncertainty.

5.4.1 Fire location and sprinkler geometry

For Scenario 1, the fire location is considered to be in the centre of the room as per the experiments. In the experimental tests, a firelighter was ignited with a propane torch in the centre of the interface between the seat and the back. However, air movement, uneven flame spread, and turbulence could have shifted the centreline of the plume over the duration of the fire, so the radial distance of the plume from the sprinkler is assumed to be normally distributed over the 400 mm width of the chair. In the experiments, the top of the seat cushion is located 0.75 m vertically from the floor. Due to the geometry of the chair, the base of the fire for modelling purposes could move as the fire progressed, spreading upward or progressing downward as the chair burned. Therefore a normal distribution with a mean of 0.75 m and a standard deviation of 0.05 m is used for the fire height parameter.

In the experiments, the sprinklers were located so that the centre of the glass bulbs were located 20 mm below the ceiling. Since the sprinkler bulbs have a length of approximately 20 mm, but the sprinkler response parameters are modelled at a point location, a normal distribution with a mean of 20 mm and a standard deviation of 5 mm is used for the bulb depth from the ceiling and truncated at 0 mm to prevent negative distances. For Scenario 2, the fire location is unknown. As an initial approximation, the plume centerline is allowed to be located anywhere within the floor area with equal probability. Realistically, this is an over simplifying assumption because room contents are not randomly located. For example, the probability of a large piece of furniture blocking a single doorway into a room is lower than it being placed in a corner or along a wall, but it provided a reasonable amount of uncertainty for the analysis here using the preliminary version of the B-RISK tool that did not have the design fire generator capabilities.

As upholstered furniture fires are only considered for Scenario 2, the fire height from the floor is taken to be a discrete distribution with probabilities of 0.3 at a height of 0 m representing floor level, 0.4 at a height of 0.5 m representing seat level, and 0.3 at a height of 1 m representing the top of the seat back. The probability that the fire would start on the seat level was estimated to be slightly higher than at the floor or top of the seat back. A summary of the distributions used to model the fire location and sprinkler geometry uncertainty is shown in Table 5.2.

Parameter	Distribution type	Distribution parameters	
	Scenario 1		
Parameter	**Distribution type**	**Distribution parameters**	
Radial distance	Normal	μ = 2 m	σ = 0.1 m
Fire height	Normal	μ = 0.75 m	σ = 0.05 m
Sprinkler distance below ceiling	Normal	μ = 20 mm	σ = 5 mm
	Scenario 2		
Parameter	**Distribution type**	**Distribution parameters**	
X and Y fire plume location (dist. from centre = $\sqrt{X^2+Y^2}$)	Uniform	Min = -2 m	Max = 2 m
Fire height	Discrete	P(H = 0 m) = 0.3, P(H = 0.5 m) = 0.4, P(H = 1 m) = 0.3	
Sprinkler distance below ceiling	Normal	μ = 20 mm	σ = 5 mm

Table 5.2: Distributions used to model fire location and sprinkler geometry uncertainty for the two scenarios considered (μ - mean, σ - standard deviation).

5.4.2 Fire heat release parameters

The BRANZFire model predicts the upper layer development and plume and ceiling jet conditions as a function of the fire heat release rate. The heat release history of a fire can be characterised as having five states: incipient, growth, flashover, fully developed burning, and decay. There is a large amount of uncertainty in the incipient time; depending on the ignition scenario it can vary from fractions of seconds to several days. During the incipient time, the heat release and fire products are minimal and there is very little risk to occupants, other than perhaps sleeping or otherwise incapable of self preservation occupants in the compartment of fire origin. For the purposes of this study, the incipient phase of the fire is ignored due to the relatively large ignition source used. Sprinklers are designed to activate during the growth period of the fire so the flashover, fully developed burning, and decay phases of the fire are not considered in this study.

A common and generally accepted design method of describing the increase in heat release rate during the growth period of the fire as a function of time for fuel controlled room contents fires is the αt^2 model. In this study, the fire intensity coefficient was used to characterise the growth rate rather than the growth time t_g which represents the time required for the HRR to reach 1055 kW (both approaches are described in NFPA 72[12]). Small fuel packages such as those used in the experiments modelled in this research will not reach 1055 kW so the fire intensity coefficient method was chosen, although the growth time can be calculated if desired. For Scenario 1, the range of growth rates is relatively easy to quantify because the

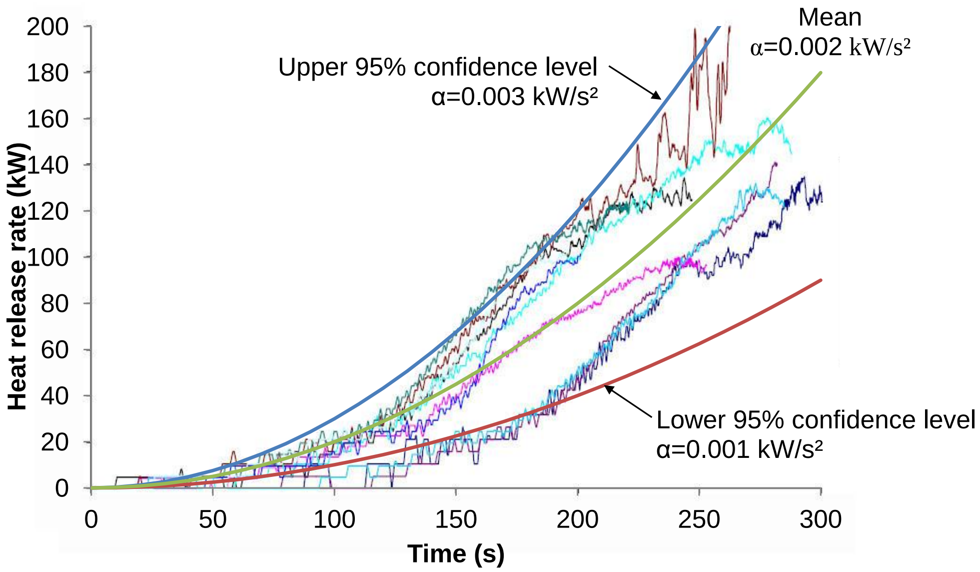


Figure 5.6: Heat release curves from Bittern's experiments[10].

model is representing a set of experiments where the HRR was calculated from the mass loss rate and effective heat of combustion. In the set of experiments, uncertainty in the mass measurement and heat of combustion contribute to uncertainty in the HRR. The load cell used in the experiments had a resolution of 5 g (error was not reported) and the cone calorimeter effective heat of combustion measurements ranged from 20.3 MJ/kg to 22.3 MJ/kg. Figure 5.6 shows the heat release curves for the experiments, as well as αt^2 heat release rate growth curves selected to approximate the mean and 95% confidence limits. A log normal distribution was used for the αt^2 growth parameter for Scenario 1. This choice of distribution corresponds with a previous study by Frantzich[13] who also used a log normal distribution for the fire growth rate, designed to account for fast and slow fires with a mean of 0.02 kW/s^2 and standard deviation of 0.01 kW/s^2.

When considering the range of fires that a room may experience over a lifetime of use for design purposes, the fire growth rate uncertainty increases. Scenario 2 considers a design scenario where the item ignited is a piece of living room upholstered furniture containing polyurethane foam. The data for the variation in fire growth rate for polyurethane furniture was obtained from a meta-study by Young[14]. The fire growth data in Young's study was obtained from a range of experimental furniture fires in furniture calorimeters. Ignition sources ranged from cigarettes to gas burners, and the frequency for each ignition source was not based on statistics from real fires. Because the data analysed by Young was from the furni-

Parameter	Distribution Type	Distribution Parameters		Source
Scenario 1 α	Log-normal	μ=0.002 kW/s^2	σ=.0005 kW/s^2	
Scenario 2 α	Log-normal	μ=.087 kW/s^2	σ=1.0895 kW/s^2	
χ_{rad}	Normal	μ=0.3	σ=0.025	

Table 5.3: Probability distributions for heat release rate parameters for both scenarios considered.

ture calorimeter, compartment effects were not included, which may influence the growth rate although the effects are expected to be small in the early fire growth stages of interest here. Therefore this distribution may not be ideal for real-world design scenarios. However, the range of fire growth rates is more realistic than selecting a single value and is useful for illustrative purposes.

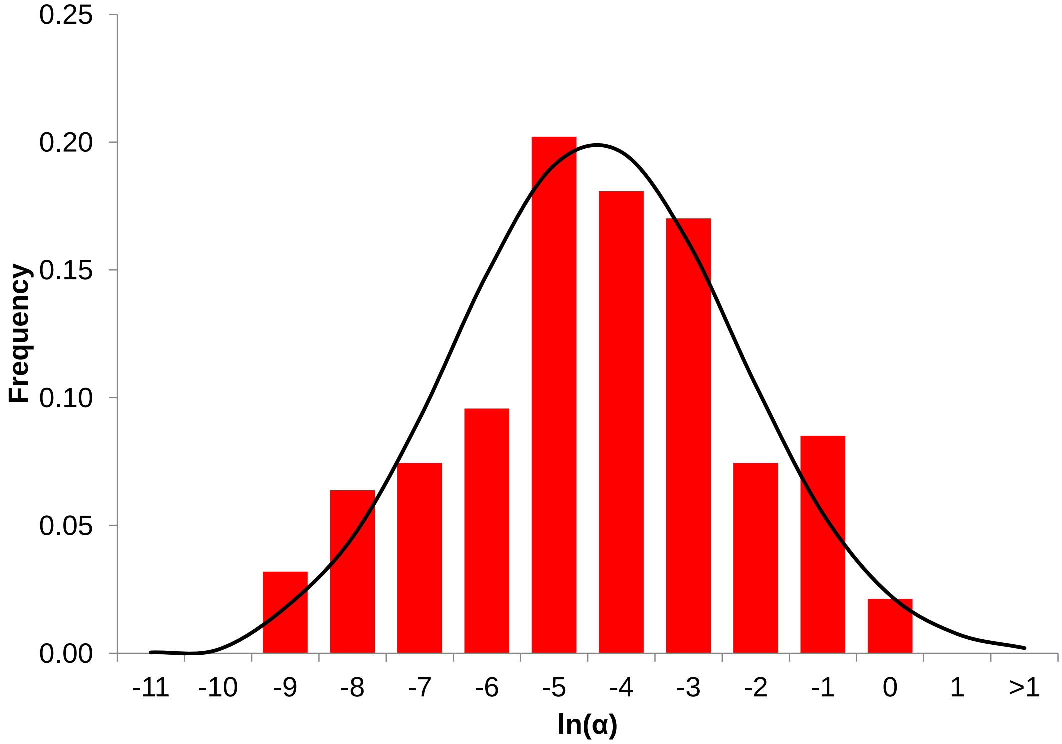
The distribution of the fire growth rate constant from Young's study is shown in Figure 5.7. A log normal distribution fit the growth rate from the study data reasonably well.

The radiative fraction of the heat release is another source of uncertainty, since the heat convected to the fire plume and ceiling jet is dependent on the amount of heat radiated from the fire. There are a range of values in the literature but no definitive study is available for upholstered furniture. Davis[5,15] has estimated the uncertainty in radiative fraction to be $\pm$ 15%, so a normal distribution is used with a mean of 0.3 and a standard deviation of 0.025. A summary of the distributions used for the fire heat release parameters can be seen in Table 5.3.

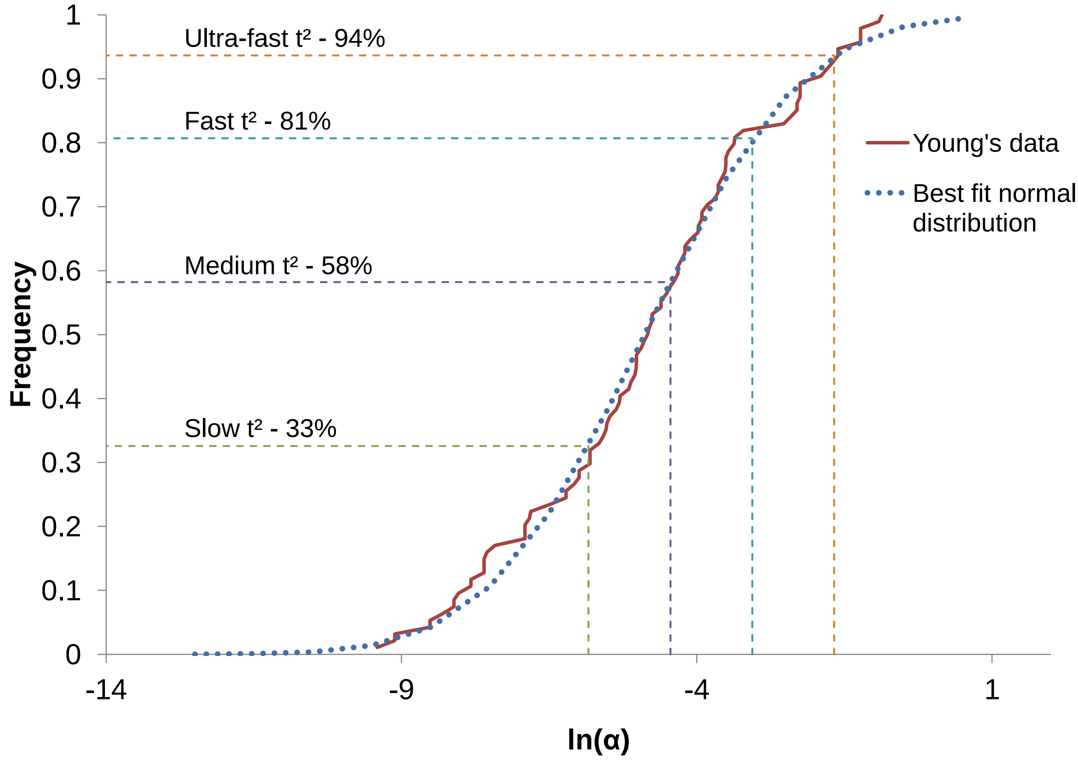
5.4.3 Sprinkler parameters

The sprinklers used for the experimental data were also used in a study to characterise the uncertainty in the response time index (RTI) and conduction (C) sprinkler parameters[16]. The sprinkler parameter study used the plunge test method under a range of wind tunnel temperature and velocity conditions in both parallel and perpendicular flow orientations.

Data on uncertainty in the sprinkler activation temperature was obtained from the study conducted by Khan[17]. A thermal liquid bath was used to slowly raise the temperature of glass bulb sprinklers until they activated. Standard response (5 mm diameter) glass bulbs of nominal 68 ^{o}C activation temperature were found to activate at a mean temperature of 72 ^{o}C with a standard deviation of 0.66 ^{o}C. A normal



(a) Probability density



(b) Cumulative probability density

Figure 5.7: Distribution of the logarithm of the heat release growth rate α, based on data from Young[14].

Parameter	Distribution Type	Distribution Parameters		Source
RTI	Weibull	α=27.2	β=96.6	[16]
C Factor	Normal	μ=0.44 $(m/s)^{1/2}$	σ=0.01 $(m/s)^{1/2}$	[16]
T_{act}	Normal	μ=72^{o}C	σ=0.655^{o}C	[17]

Table 5.4: Distributions for the uncertainty in sprinkler parameters, used for both scenarios.

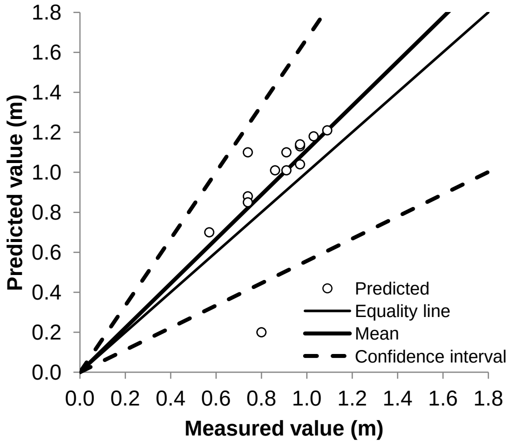
distribution with these parameters was used to model the activation temperature uncertainty. A summary of the sprinkler parameter distributions is shown in Table 5.4.

5.4.4 Model uncertainty

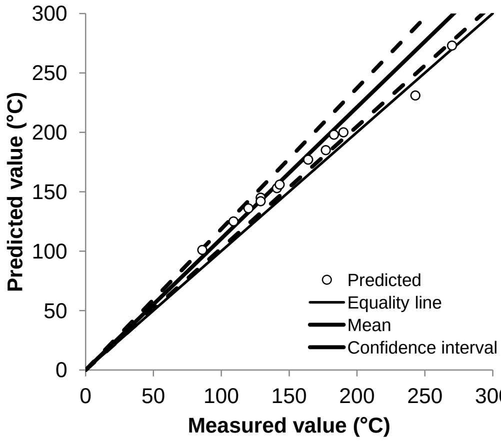
Uncertainty in model predictions for the plume temperature, upper layer temperature, and layer height were considered because the JET model calculation for sprinkler activation time depends on these quantities. Estimates of the model uncertainty in calculating the layer height and upper layer temperature were made from the BRANZFire verification data [11]. The BRANZFire verification data includes comparisons to 62 kW to 158 kW fires in a 2.8 m by 2.8 m by 2.13 m tall room with various vent configurations using experiments reported by Steckler[18]. Figure 5.8 compares the BRANZFire model output to the experimental results cited in the verification report.

From this data, distributions for the model uncertainty in layer height and upper layer temperature were produced. A multiplicative error likelihood model was used[19] because any error in layer height or temperature was assumed to accumulate as time progressed. The model calculations for layer height and upper layer temperature are multiplied by an uncertainty factor, which is sampled from the distributions and added as an input parameter to the input file.

An uncertainty distribution for the plume temperature submodel output was estimated from the study by Sheppard and Meacham[20]. They found a 95% confidence interval of 41.6 ^{o}C with a model similar to the JET model. As per Sheppard and Meacham's findings, an additive error likelihood model[19,21] was used, where an uncertainty factor sampled from the distribution is added to the BRANZFire plume temperature calculation. Table 5.5 summarises the model uncertainty distributions used in this study.



(a) Layer height



(b) Upper layer temperature

Figure 5.8: Comparisons of BRANZFire model predictions to experiment data from Wade's verification report[3].

Parameter	Distribution Type	Distribution Parameters		Source
Layer Height	Normal	μ=111%	σ=28%	
Upper Layer T	Normal	μ=111%	σ=8%	
Plume T	Normal	μ=0^{o}C	σ=20.8^{o}C	

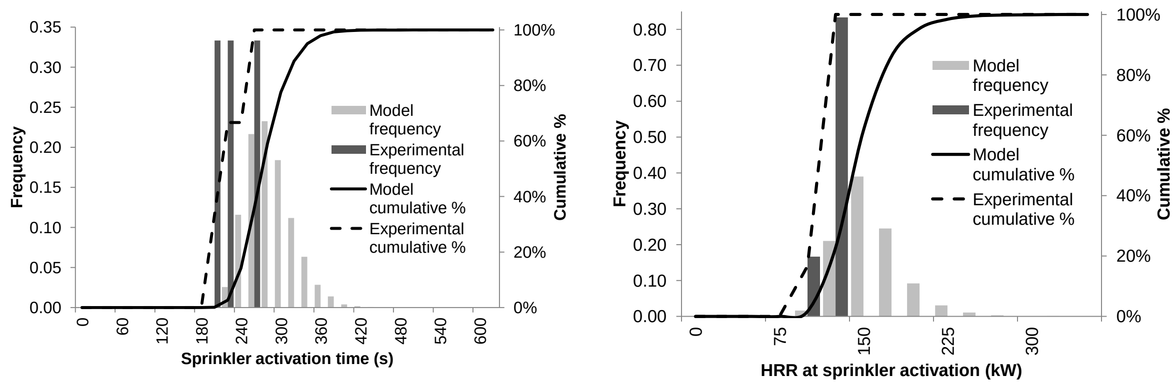
Table 5.5: Distributions used for model uncertainty

5.5 Results and discussion

The modelled sprinkler activation time had a mean time of 276 s with a standard deviation of 35 s in Scenario 1. Compared to the experimentally measured sprinkler activation times [18], the mean time was 40 s longer and the standard deviation was 9 s greater in the model. The mean HRR at the time of activation from the model was 146 kW (compared to 124 kW experimentally) with a standard deviation of 29 kW (compared to 28 kW experimentally). The experimental statistics had a large margin of error due to the small sprinkler activation sample size of six, but the results matched reasonably well as shown in Figure 5.9. The model tended to over-predict both sprinkler activation time and HRR at the time of sprinkler activation.

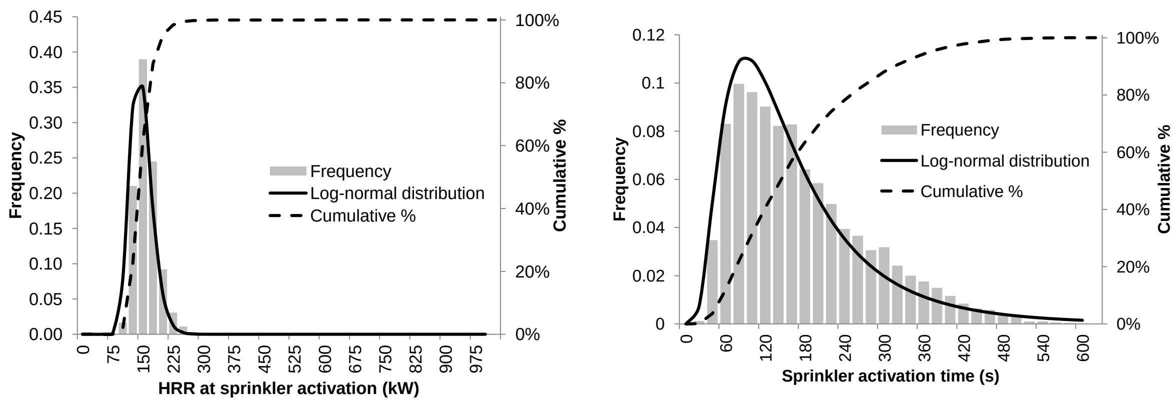
The uncertainty in sprinkler activation time for the two scenarios can be seen in Figure 5.10. Best-fit log-normal distributions are also plotted. There was significantly more uncertainty in Scenario 2 as expected.

A tornado chart ranking the sensitivity of the modelled sprinkler activation



(a) Sprinkler activation time (b) HRR at sprinkler activation

Figure 5.9: Comparison of Scenario 1 experimental and model results.

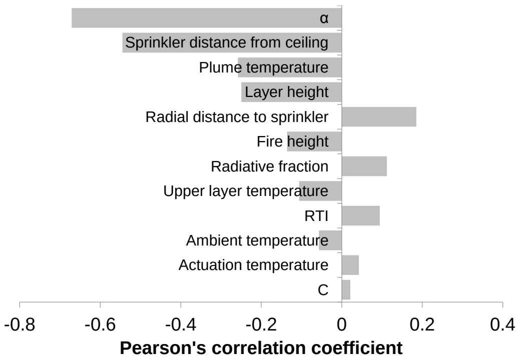


(a) Scenario 1 (b) Scenario 2

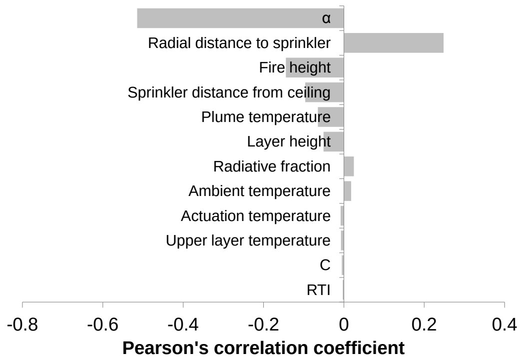
Figure 5.10: Sprinkler activation time distributions for Scenarios 1 and 2.

time to the sources of uncertainty is shown in Figure 5.11. For both scenarios, the heat release growth rate parameter α was the largest contributor to the uncertainty in the sprinkler activation time. A negative value for the Pearson's correlation coefficient indicates a negative relationship between the input and output parameter. As expected, if the fire grows faster (an increase in α), the sprinkler activation time decreased.

The sprinkler activation time was also sensitive to the distance of the sprinkler from the ceiling, due to the vertical distribution of ceiling jet temperature and ve-



(a) Scenario 1



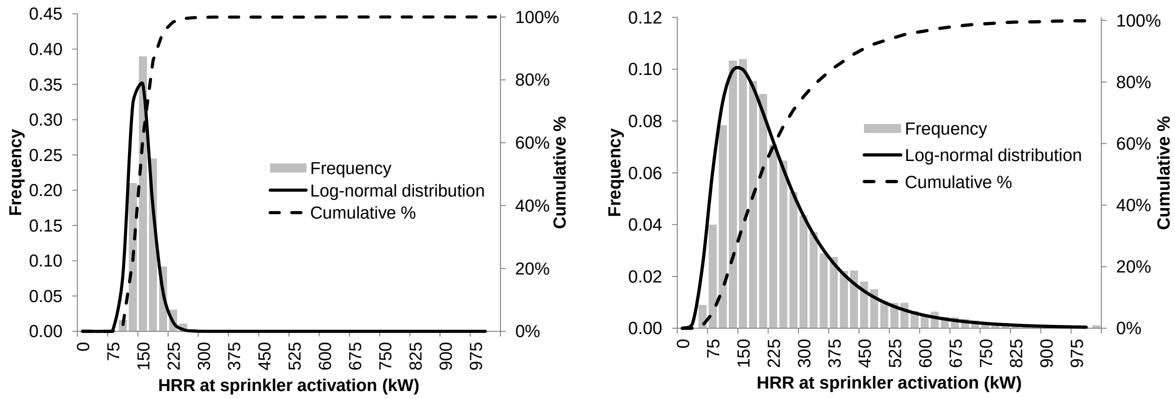
(b) Scenario 2

Figure 5.11: Tornado charts comparing sprinkler activation time sensitivity to sources of uncertainty for Scenarios 1 and 2.

locity. The relative importance of the model uncertainty sources decreased as the uncertainty in α and the fire location increased from Scenario 1 to Scenario 2. The uncertainty in sprinkler parameters and the ambient temperature had little influence on the sprinkler activation time.

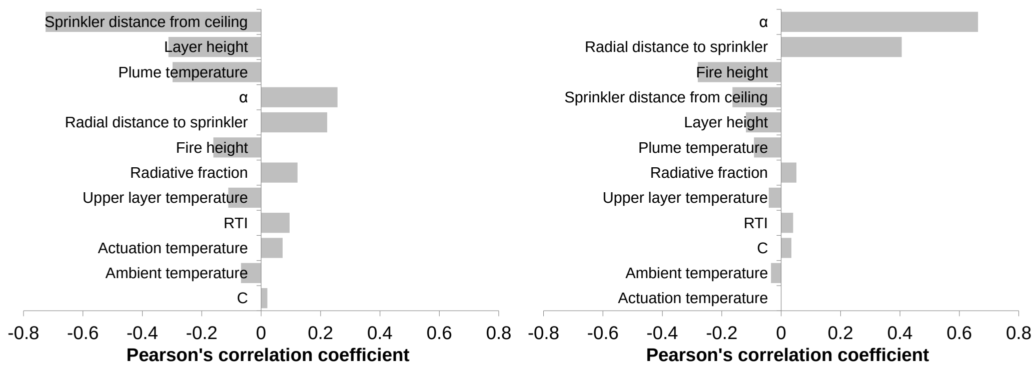
Figure 5.12 shows the uncertainty in the HRR at the time of sprinkler activation time for the two scenarios. Scenario 2 has much more uncertainty than Scenario 1. Figure 5.13, which is a tornado chart ranking the sensitivity of the heat release rate at sprinkler activation to the quantified sources of uncertainty, shows that the major source of uncertainty for Scenario 1 is the sprinkler distance from the ceiling, due to the variation in temperature and velocity in the ceiling jet with height. The model uncertainty has a relatively large impact for Scenario 1, as the layer height uncertainty and the plume temperature uncertainty are ranked second and third, respectively. An increase in α causes the HRR to grow faster so as expected it has a positive effect on the HRR at the time of sprinkler activation, but the effect is offset by the tendency for the sprinkler to activate sooner. For Scenario 2, the uncertainty in α and fire location takes precedence, while the model uncertainties are of less consequence. For both scenarios, the uncertainty in sprinkler parameters and ambient temperature are the least influential on the HRR outcome.

For both output parameters considered in this study, the increase in uncertainty in the fire growth and location reduced the relative importance of the model



(a) Scenario 1 (b) Scenario 2

Figure 5.12: Heat release rate distributions at the time of sprinkler activation for Scenarios 1 and 2.



(a) Scenario 1 (b) Scenario 2

Figure 5.13: Tornado charts comparing the sensitivity of the heat release rate at sprinkler activation time to sources of uncertainty for Scenarios 1 and 2.

certainty or accuracy. A more accurate but more complex and computationally expensive model will not provide more useful information for the model user if the model uncertainty is significantly less than the aleatoric uncertainty. An efficient model will provide a ”consistent level of crudeness,” balancing model uncertainty with aleatoric uncertainty. On the other hand, if the model inputs are well known for a specific situation, a complex model may well be justified.

5.5.1 Sources of uncertainty not considered

There are many sources of uncertainty that are difficult to quantify. For instance, a number of assumptions are made in the BRANZFire zone model and associated submodels. As a zone model does not solve the momentum equation the combustion product transport time is assumed to be negligible. BRANZFire uses the LAVENT model for the vertical temperature and velocity distribution of the ceiling jet, and there is no data to indicate the level of uncertainty for these parameters. BRANZFire also makes the assumption of homogeneous temperature and combustion products in the layers, the effect of which is difficult to quantify. An advantage of using a field model is the ability to model these aspects, although other sources of uncertainty will come into play with field models, such as uncertainty in the turbulence models.

By using model verification data to create uncertainty distributions for the model, the uncertainty in many of these assumptions is included implicitly. It is expected that as a model is pushed beyond the situations for which it has been verified, the uncertainty in the model will grow and become impossible to quantify. Therefore, models should only be used within their limits where the uncertainty can be quantified and compared to the aleatoric uncertainty.

Other model input parameters, such as the thermal properties of the wall, ceiling, and floor linings, were modelled as single values and uncertainty was not considered because it was not expected to have a significant impact on the uncertainty of the outputs. Ventilation conditions could also be modelled as an uncertain parameter for the design scenario. In this case the door was modelled as being open all the time.

For the purposes of this study, all sources of uncertainty have been assumed to be independent. No correlations between parameters have been considered, due to a lack of data to support them. The uncertainty in the output variables would likely increase if correlations were included.

5.5.2 Conclusions

The importance of sources of uncertainty depends on the situation being considered. The accuracy of the model becomes less important as the fire and geometry parameters become less well defined. For the output and scenarios considered, uncertainty in the sprinkler response parameters provided little influence on the outcome. The BRANZFire zone model uncertainty was not the most influential source of uncertainty for the scenarios modelled, and became less important for Scenario 2 where the uncertainty in the fire growth and location was greater.

Model uncertainty should be considered when using computer fire models. While the increase in available computing resources allows more complex models to be used in probabilistic Monte Carlo simulations[22], a more complex model can introduce additional sources of uncertainty; particularly user decision uncertainty. In order to quantify the model uncertainty, the model must be used within reasonable parameters. If the model is used beyond its limits, the uncertainty in the output becomes unknown and should not be trusted. The model complexity should be matched to the level of certainty in the situation being modelled.

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CHAPTER 6

TEMPERATURE RESPONSE OF MODIFIED SPRINKLERS

6.1 Introduction

Fire sprinklers operate as heat detectors, but they only provide one data point in their response to heating: the time of activation, when they have been heated to their activation temperature and either the glass bulb element breaks or a solder link melts. A nominal value for activation temperature is available from the manufacturer, but there has been shown to be uncertainty in the actual activation temperature of glass bulb sprinklers when heated slowly in a stirred liquid bath[1]. In order to measure the temperature response of a sprinkler during the time leading up to activation, a method to insert a thermocouple into a modified glass bulb mounted in a sprinkler frame was developed. This chapter describes the characterisation of the thermal response of the modified thermocouple-equipped sprinklers. The response was evaluated experimentally using both wind tunnel plunge tests and fires in an ISO 9705 compartment, and compared to the thermal detector response correlation by Heskestad and Bill Jr.[2] and B-RISK and BRANZFire simulations of one of the ISO 9705 compartment fires.

6.2 Literature review

Two other studies attempted to represent the thermal response of a sprinkler head using brass or aluminum cylinders with thermocouples inserted[3,4]. Ingason[5] attempted to measure the temperature change of a glass bulb when it was removed from a furnace, but the bulb was not mounted in a sprinkler frame. The SFPE evaluation of the DETACT-QS fire model for estimating sprinkler activation times describes the use of brass disc thermocouples to approximate thermal detector elements in a ceiling jet[6]. The plunge test method used was described in a previous University of Canterbury study[7,8] and is briefly described in Section 6.4.2.

The primary source of heat transfer to sprinklers in fires is usually considered to be convective heat transfer from the ceiling jet flow, and can be affected by the orientation of the yoke arms. A numerical simulation on heat transfer to sprinkler glass bulbs conducted by Ingason and Persson[9] estimated that heat transfer to a sprinkler bulb was decreased by a factor of two when the sprinkler frame arms were oriented parallel to the flow, relative to the opposite case where the sprinkler frame arms were oriented perpendicular to the flow.

6.3 Theory

Heskestad and Bill Jr.[2] developed a two parameter model for heat detector temperature response, which accounts for convective heat transfer from a hot gas stream to the heat detector and conductive losses through the detector fixture. Heskestad's model is as follows:

$$\frac{d\Delta T_d}{dt} = \frac{\sqrt{u}}{RTI}\left[\Delta T_{gas} - \left(1 + \frac{C}{\sqrt{u}}\right)\Delta T_d\right] \tag{6.1}$$

where ΔT_d is $T_d - T_{amb}$ and ΔT_{gas} is $T_{gas} - T_{amb}$, respectively. For a plunge test, where the gas velocity and temperature are constant, this equation can be rearranged as follows:

$$\Delta T_d = \frac{\Delta T_{gas}}{1 + \frac{C}{\sqrt{u}}}\left[1 - e^{\frac{-t\sqrt{u}\left(1+\frac{C}{\sqrt{u}}\right)}{RTI}}\right] \tag{6.2}$$

to obtain the detector temperature as a function of time. To compare with standard sprinkler plunge test results where the information on the detector temperature response is the time of activation and the activation temperature the equation can be rearranged to solve for the RTI given activation time:

$$RTI = \frac{-t\sqrt{u}}{\left(1+\frac{C}{\sqrt{u}}\right)^{-1} \cdot ln\left[1 - \frac{\Delta T_d}{\Delta T_{gas}\left(1+\frac{C}{\sqrt{u}}\right)^{-1}}\right]} \tag{6.3}$$

Heskestad's equation was suitable for the wind tunnel tests because there was no large radiant heat source available. Sako and Hasemi[10] indicated that radiant heating may be a factor for a sprinkler in close proximity to a fire and added a corresponding term to the energy balance:

$$\frac{d\Delta T_d}{dt} = \frac{\sqrt{u}}{RTI}\left[\Delta T_{gas} - \left(1+\frac{C}{\sqrt{u}}\right)\Delta T_d\right] + C_r\left(\dot{q}_e^{''} - \sigma T_s^4\right) \tag{6.4}$$

where C_r is a radiation responsiveness parameter, $\dot{q}_e^{''}$ is the external radiation flux, and σ is the Stefan-Boltzmann constant. Sako and Hasemi estimated the C_r value to be 0.21 $\frac{Km^2}{kJ}$ for the nominally 120 $m^{1/2}s^{1/2}$ RTI fused-link sprinklers they tested.

6.4 Apparatus setup

6.4.1 Sprinkler modifications

Modified 5 mm diameter glass bulbs were constructed by the University of Canterbury glass shop. Figure 6.1 shows the modified sprinkler head, along with the components of a Viking VK102 sprinkler head. In a frangible bulb sprinkler such as the one pictured, the glass bulb is held against a brass seal by a set screw. The modified sprinkler bulbs had one open end which was placed towards the seal.

Attempts were made to use both Viking and Tyco sprinkler frames. The Tyco frames did not work because the set screws were adhered in place too tightly and could not be removed without damage. The set screws were also glued in the Viking frames using some sort of thread compound, but the screws could still be removed with some heat application from a butane torch without damaging the frame, screw, or bulb. Viking VK102 and VK302 frames were used because they were available at the university. They are standard response, pendent, 1/2″ national pipe thread

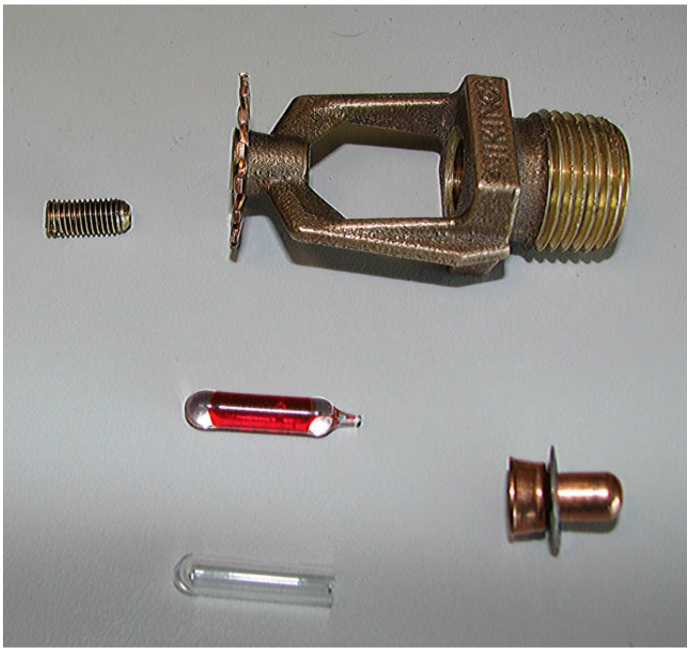


Figure 6.1: Sprinkler head components, including standard components from a Viking VK102 sprinkler head and the modified glass sprinkler bulb.

(NPT) spray sprinklers with a nominal K-factor of 5.6 $\frac{l/min}{\sqrt{kPa}}$ [11]. The brass sprinkler seal was drilled to allow the thermocouple to pass through.

The thermocouple was extended approximately half way into the glass bulb as shown in Figure 6.2. The glass bulb was filled with glycerine, which is the fluid indicated by one manufacturer's Materials Safety Data Sheet for a 5 mm standard response bulb[12].

6.4.2 Plunge test and wind tunnel setup

The University of Canterbury wind tunnel shown in Figure 6.3 was used to provide a stream of heated air at approximately constant temperature and velocity. A more detailed description of the wind tunnel and its performance characteristics can be found in Tsui's thesis[8]. The wind tunnel used a frequency drive variable speed fan to provide a range of air velocities. The wind tunnel was run at nominally 120^{o}C for all of the tests discussed in this research. The velocity of the air at the height of the sprinkler frame was measured with a pitot static tube, and was approximately 2.7 m/s at the fan drive frequency of 45 Hz that was used for all of the tests conducted for this work.

Figure 6.2: The modified sprinkler head, showing the thermocouple inserted in the glass bulb.

The University of Canterbury wind tunnel was set up to test sprinklers in the pendant orientation. The method of construction of the glass bulb may make testing in an upright orientation more difficult because attaining a seal between the cut end of the glass bulb and the sprinkler seal would be challenging and thus it would be difficult to prevent the sprinkler bulb fluid from leaking out.

For the wind tunnel tests, the sprinkler was mounted to a fixture to allow it to be plunged into the wind tunnel, shown in Figure 6.4. The fixture was constructed of 19 mm plywood with a brass pipe installed. The sprinkler was mounted approximately 10 mm from the bottom surface of the plywood, which was marked in 5^o increments for changing the orientation angle of the sprinkler to the air flow in the wind tunnel, as shown in Figure 6.5.

The thermocouple wire had to be sealed where it passed through the seal because some of the tests were run with water in the sprinkler to include as much of the heat conduction loss experienced by a normal sprinkler as possible. Attempts to seal the thermocouple wire with RTV type silicone sealant proved fruitless so a section of copper tubing long enough to surpass the water level was brazed to the brass seal, as shown in Figure 6.4. Water was then added to the annular space around the copper tubing to include conduction losses to the water above the sprinkler. The

Figure 6.3: The University of Canterbury wind tunnel was used to provide the plunge test conditions for testing the modified sprinkler thermal response characteristics.

water temperature was measured prior to and after each test and the water was replaced for each test.

The thermocouple output was logged using the University of Canterbury's Universal Data Logger (UDL) setup which was set for a sample rate of approximately 2 samples/s and a resolution of 0.5^{o}C for the thermocouple output. The actual sample rate was found to be 1 sample/0.55 s from the datalogger's time stamp.

6.4.3 Compartment fire test setup

Four sprinklers containing the modified and standard response bulbs were installed in compartment fire tests conducted as part of the project to evaluate the item-to-item design fire generator[13]. As the sprinkler objectives were supplementary to the primary design fire generator validation goals, the room geometry, item location, and fire decisions were driven by the design fire generator requirements rather

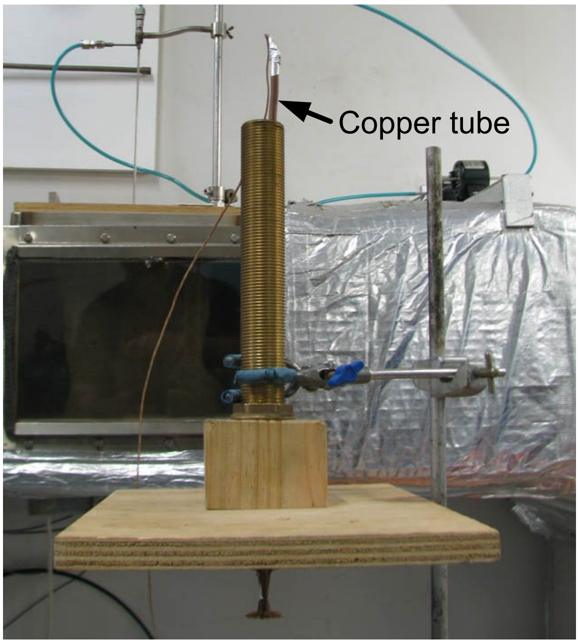


Figure 6.4: The sprinkler plunge fixture was constructed of 19 mm plywood with a brass pipe fixture to thread the sprinkler into and contain water.

than tailored for the sprinkler tests. An ISO 9705 room fire compartment with a calorimeter hood was used for the tests. The rooms contained three types of items representing residential furniture including a polyurethane armchair, a MDF table, and an ABS flat panel television. The items were arranged in four different configurations. Five scenarios were tested: the first four used a steady 100 kW propane burner as the first item ignited with the different item configurations, and the final scenario used the fourth configuration (D) with an ethanol pool as the first item ignited.

The configuration of the ceiling jet thermocouple and bi-directional velocity probe and standard and modified sprinklers in the ISO 9705 room is shown in Figure 6.7. The height of the room was 2.4 m as per the ISO 9705 standard. The sprinklers were named as per the following convention:

- SPA - standard sprinkler, yoke arms parallel to the room axis
- MPA - modified sprinkler, yoke arms parallel to the room axis
- MPE - modified sprinkler, yoke arms perpendicular to the room axis
- SPE - standard sprinkler, yoke arms perpendicular to the room axis

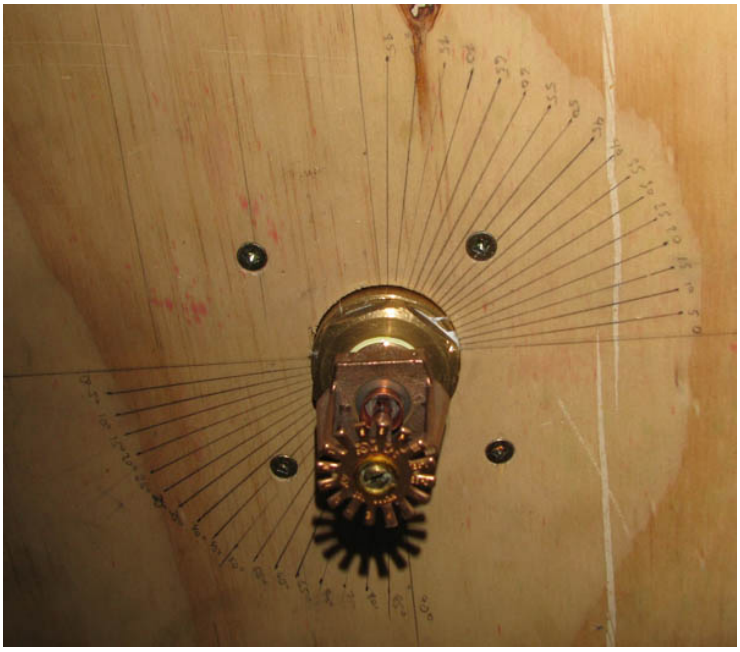


Figure 6.5: The sprinkler was mounted approximately 10 mm from the bottom of the plunge fixture plywood which was marked in 5^o increments.

The sprinklers were mounted 800 mm from the doorway with the deflectors 115 mm from the room ceiling. A photo of the sprinkler installation is shown in Figure 6.6.

Sprinklers SPA and SPE were standard response Tyco 3251 pendant sprinklers with nominal activation temperatures of 68^oC. These sprinklers were connected to piping that was gravity filled with water to simulate typical thermal conduction conditions that would be present in a wet sprinkler system. The piping was then charged with compressed air to approximately 350 kPa. Automotive oil pressure switches that opened at approximately 35 kPa were connected to the data acquisition system and used to record the activation time. The change in resistance across the switch from the open to closed position was used as the indication of activation. The activation time was also verified visually and recorded with a stopwatch. The standard sprinklers were replaced, recharged, and pressure tested after each experiment.

Sprinklers MPA and MPE had the modified sprinkler bulbs with thermocouples installed. The modified sprinkler bulbs were cleaned and refilled with glycerine before each test. A thermocouple was also installed 880 mm from the doorway on the centreline of the room and 80 mm down from the ceiling to measure the ceil-

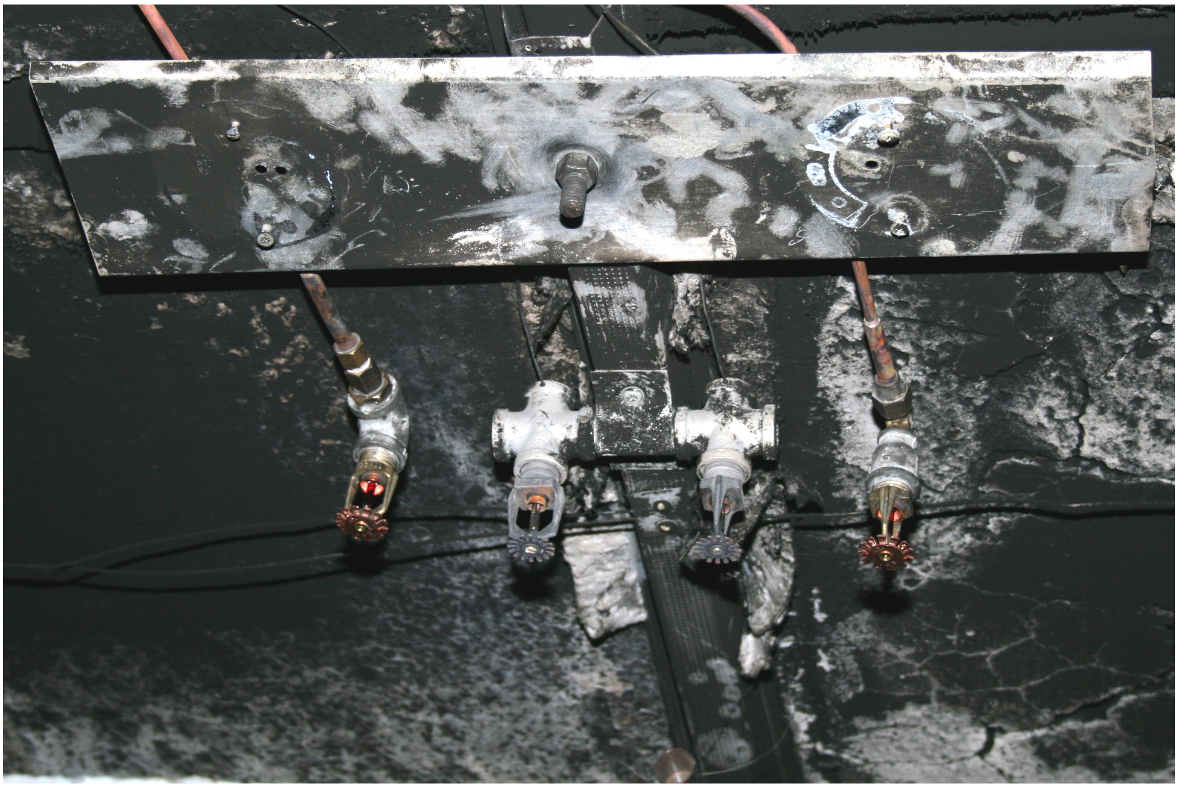


Figure 6.6: Sprinklers installed for a ISO 9705 compartment fire test. The sprinklers on the outside were as manufactured, while the centre sprinklers had modified glass bulbs with thermocouples installed.

ing jet temperature. A bi-directional velocity probe was installed 1080 mm from the doorway on the centreline of the room and 105 mm from the ceiling to measure the ceiling jet velocity. It was orientated horizontally in the direction of the centreline of the room. The measured values were recorded at 3 s intervals by the data acquisition system. The sprinkler and instrumentation layout is shown in Figure 6.7.

The four configurations of the items in the room and the burner are shown in Figure 6.8. The 100 kW propane burner was located near the centre of the room for scenario A, and was located in the corner for scenario B. A photo of the burner flame in scenario A is shown in Figure 6.9. The flame height was nearly at the ceiling. The exact locations of the burner and items were driven by the main objective of the experiments which was to evaluate the item-to-item fire spread capabilities of the model, and were not chosen for optimal sprinkler thermal response. Due to the lack of other items igniting in scenario B, the burner was moved closer to armchair 3 for scenario C. This resulted in armchair 3 igniting, but no further fire spread, so armchairs 1 and 2 and MDF cube 1 were moved closer to the other items for scenario

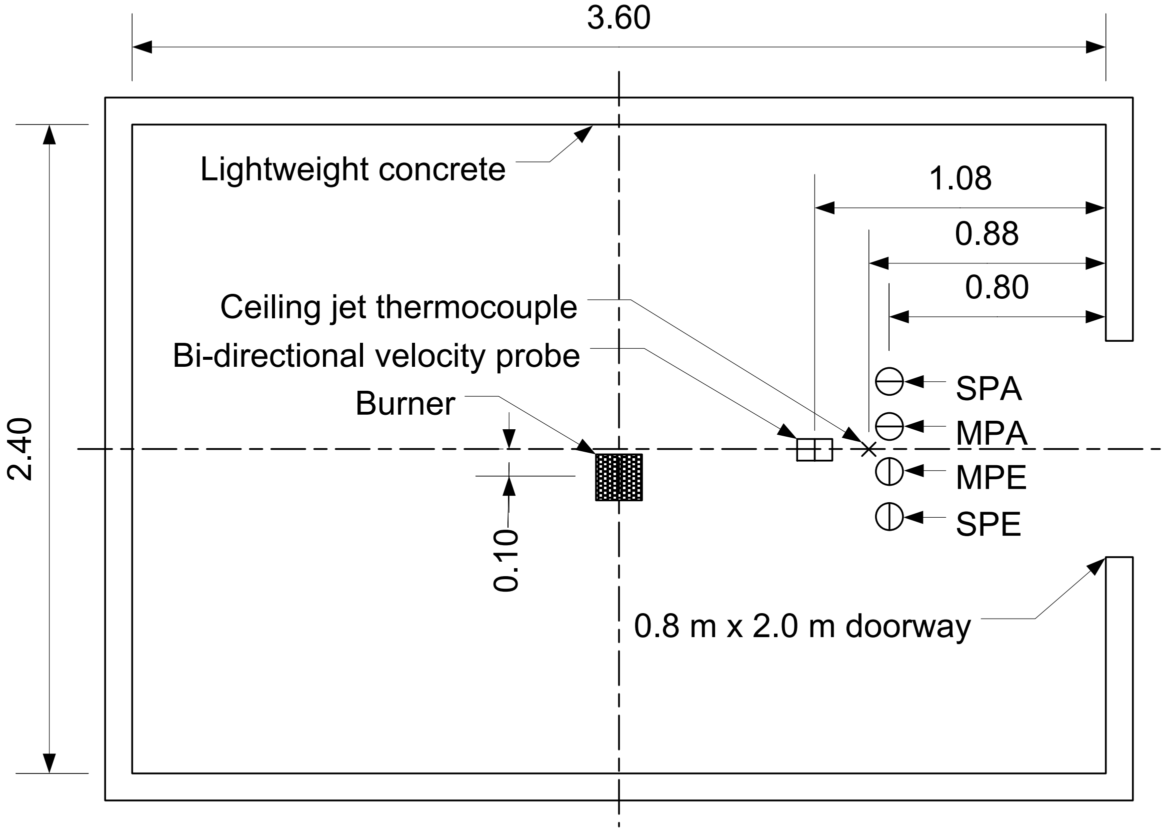


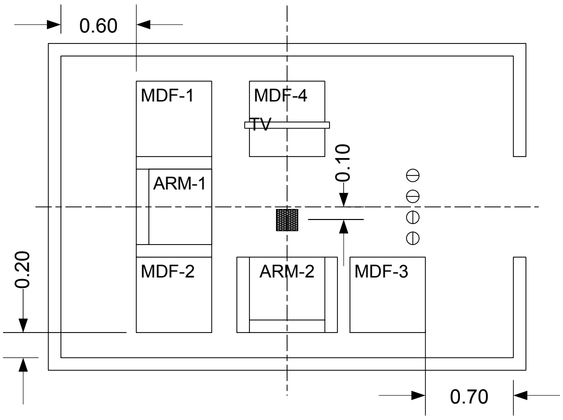
Figure 6.7: Layout of the sprinklers and ceiling jet instrumentation in the ISO 9705 room. The propane burner is shown for reference. All dimensions are in m.

D. The propane burner used was the standard ISO 9705 burner. For scenario E, a 10 cm square pan containing 120 mL of ethanol was placed on the propane burner adjacent to the edge of armchair 3.

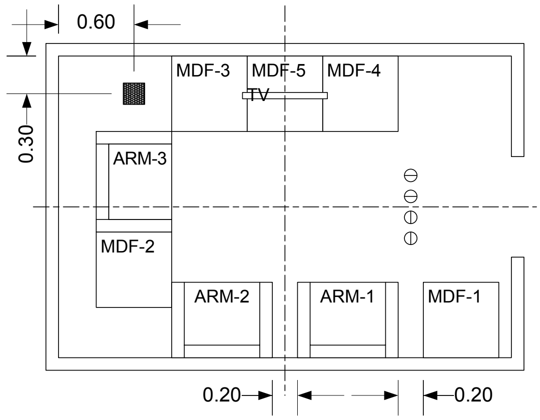
6.5 Plunge test results

6.5.1 Comparison between Heskestad's model and the plunge test experiments

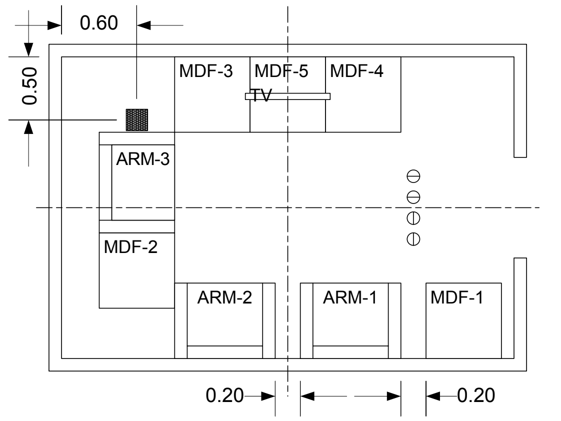
The RTI for the sprinkler response for each plunge test was calculated using Equation 6.3. To compare the results to Tsui's study, the RTI was calculated when the thermocouple reached 68^{o}C. The RTI was then used in equation 6.2 to calculate predicted temperature response as a function of time, as shown in Figure 6.10. The shape of the measured temperature response matched the model predictions well.



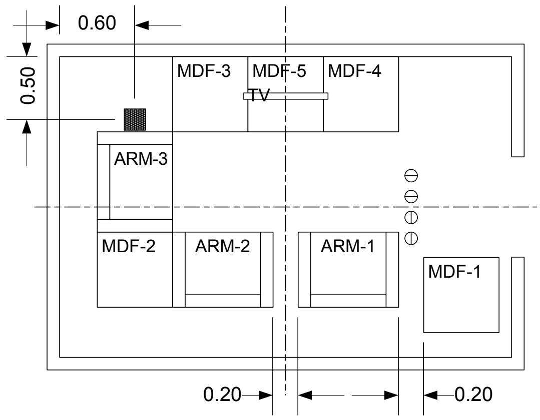
(a) Scenario A



(b) Scenario B



(c) Scenario C



(d) Scenario D and E

Figure 6.8: Item layout for the five compartment fire scenarios. The item names are shown. All dimensions in m.

6.5.2 Sprinkler orientation

Plunge tests were conducted with orientations from 90^o (sprinkler yoke arms perpendicular to the flow) to 0^o (sprinkler yoke arms parallel to the flow). From Tsui's results, the detector response was expected to not change between 90° and 45°, and then start increasing somewhere between 45° and 0°. Therefore, plunge tests were conducted at 90° and in 5° increments from 45° to 0°.

A plot of the effect of orientation on the RTI parameter can be seen in Figure 6.11. The RTI increased from approximately 90 m s$^{1/2}$ to approximately 100 m s$^{1/2}$ from perpendicular orientation to parallel. It was observed that the thermal response for the sprinkler near 45° was not repeatable and fluctuated more than for

Figure 6.9: Propane burner in scenario A location for the ISO 9705 compartment fire test. The top of the flame was nearly at the compartment ceiling.

the parallel or perpendicular orientations.

6.5.3 Effects of water on modified sprinkler thermal response

A total of 11 tests were run in the parallel orientation, including three with no water above the sprinkler and eight with water. The RTI for each run was calculated as previously described. Histograms for the wet and dry cases are shown in Figure 6.12. The uncertainty in RTI was similar to what Ruffino calculated for cylinders representing sprinklers, with a 95% confidence interval of ± 22 (m s)$^{1/2}$. The mean RTI was 108 (m s)$^{1/2}$.

Even with water added, the RTI in the parallel orientation was less than the value reported by Tsui, which was nominally 160 (m s)$^{1/2}$ for a similar sprinkler head. It appeared that the effect of the deflector arms in the path of the flow around the sprinkler bulb did not only slow down the convective heat transfer to the bulb, but also caused other effects such as potentially delaying the bulb rupture to higher temperatures.

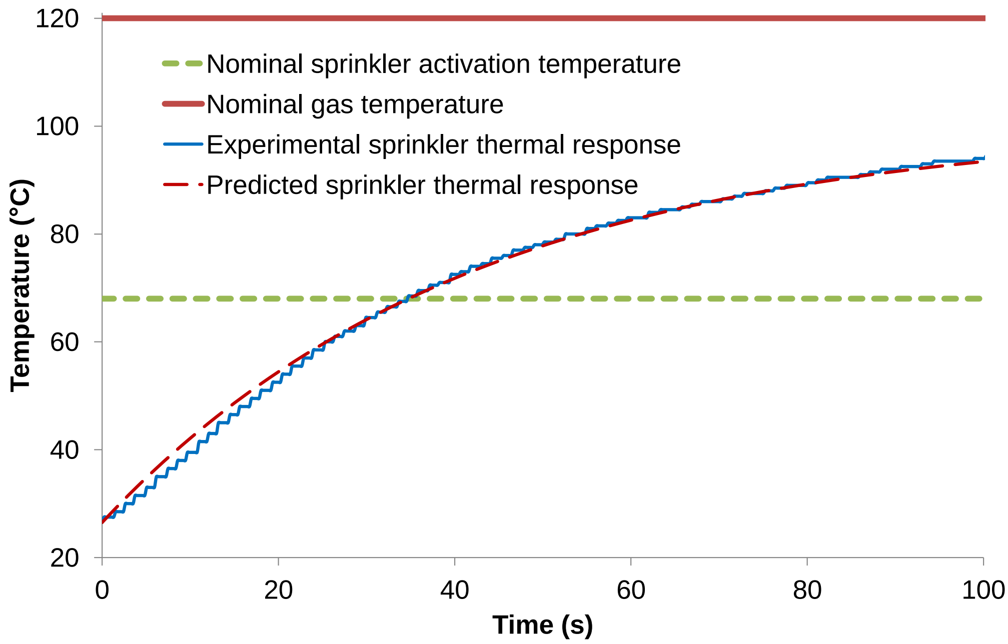


Figure 6.10: Comparison between experimental and modelled thermal response for a modified sprinkler in the perpendicular orientation.

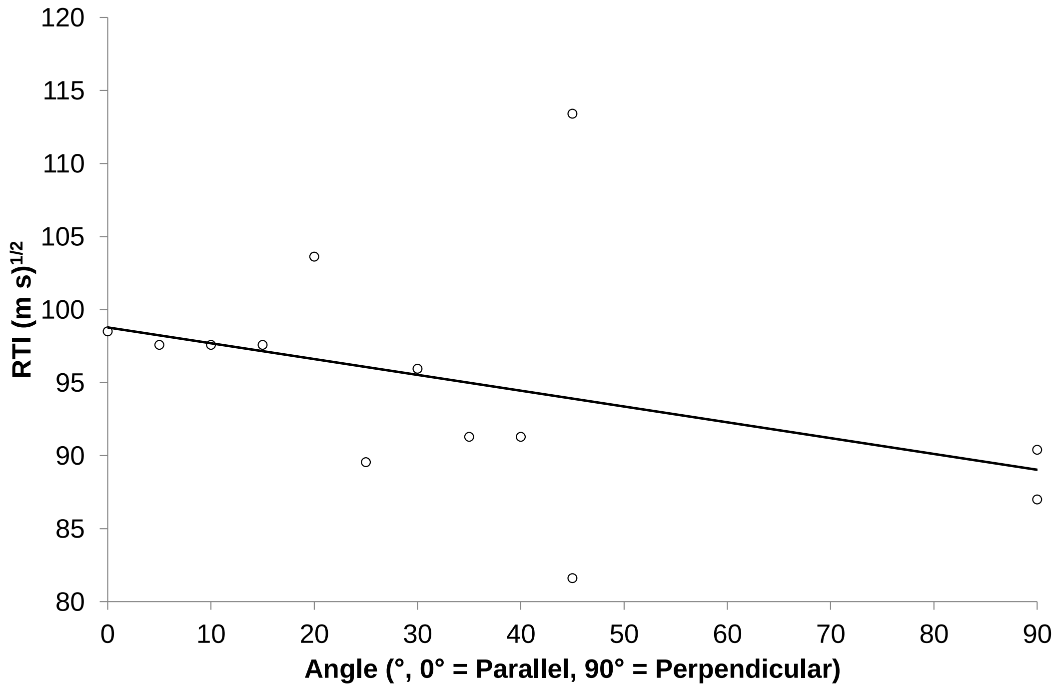


Figure 6.11: Effect of sprinkler orientation on modified sprinkler RTI.

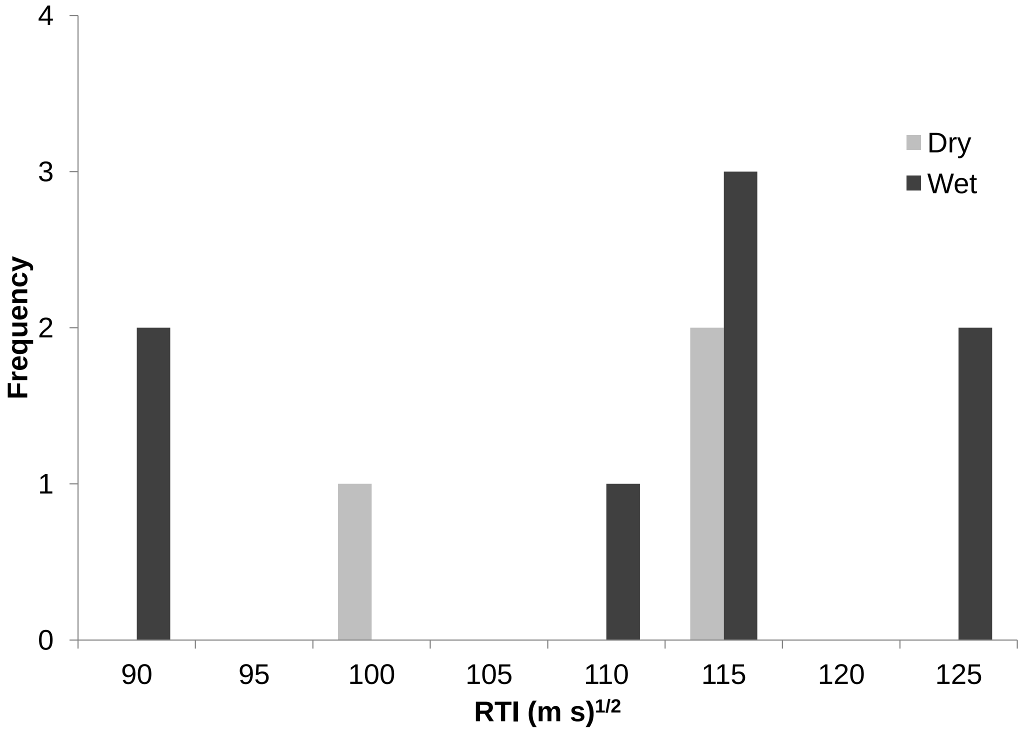


Figure 6.12: Histograms for parallel orientation plunge test results with wet and dry sprinkler pipe.

6.6 Compartment fire test results

6.6.1 Modified sprinkler response

The sprinkler activation times for the standard sprinklers and the temperatures of the modified sprinklers at the time of activation for the standard response sprinkler with the same orientation are shown in Table 6.1.

As discussed in Chapter 5, Khan et al[1] found that sprinklers with standard response 5 mm bulbs and nominal activation temperatures of 68^{o}C activated at a mean temperature of 72^{o}C with a standard deviation of 0.655^{o}C when immersed in a uniformly heated water bath. Histograms of the modified sprinkler temperature at the time of standard sprinkler activation are shown in Figure 6.13.

The temperature measured at activation for the parallel sprinklers was on average 5^{o}C greater than the temperature measured at activation for the perpendicular

Experiment	SPE act. time (s)	MPE T (^oC) @ SPE act. time	SPA act. time (s)	MPA T (^oC) @ SPA act. time
A1	81	80.2	90	70.1
A2	48	72.4	96	83.3
A3	39	70.0	60	86.4
B1	54	71.2	66	77.5
B2	54	76.8	72	82.8
C1	57	71.9	60	70.7
D1	44	73.2	62	76.1
D2	50	76.1	65	82.1
D3	60	70.6	66	76.8
E1	209	73.7	239	79.9
E2	180	71.1	216	78.5
Mean		**73.4**		**78.6**
St. dev.		**3.1**		**5.1**

Table 6.1: Activation times for standard sprinklers in the ISO 9705 compartment fire tests and the temperature of the modified sprinklers at the time of activation for the standard sprinkler with the same orientation.

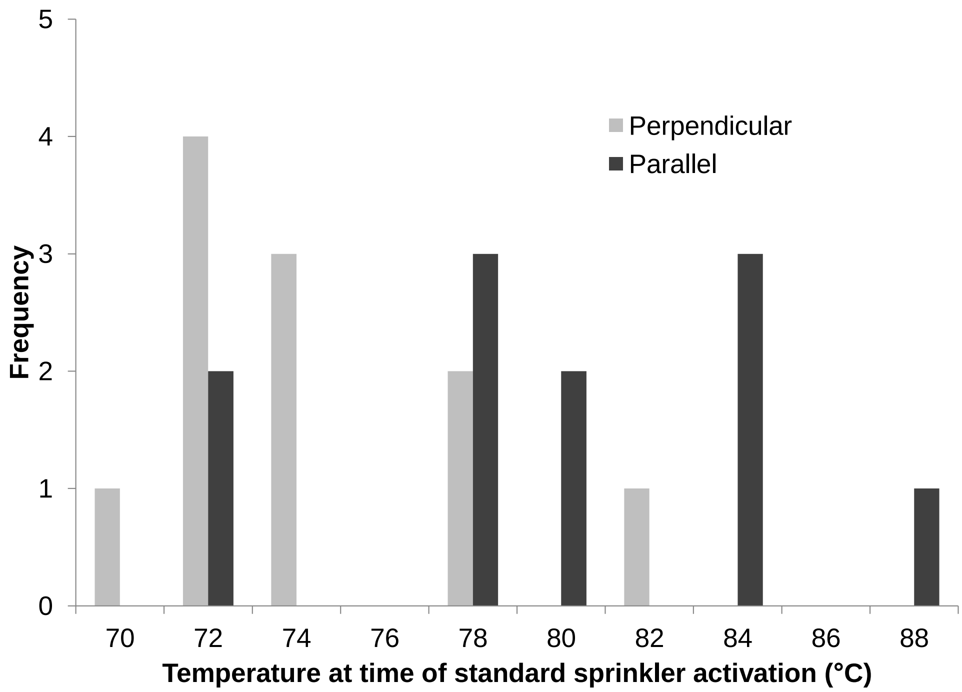


Figure 6.13: Histograms of the modified sprinkler temperature at the activation time of the standard sprinklers.

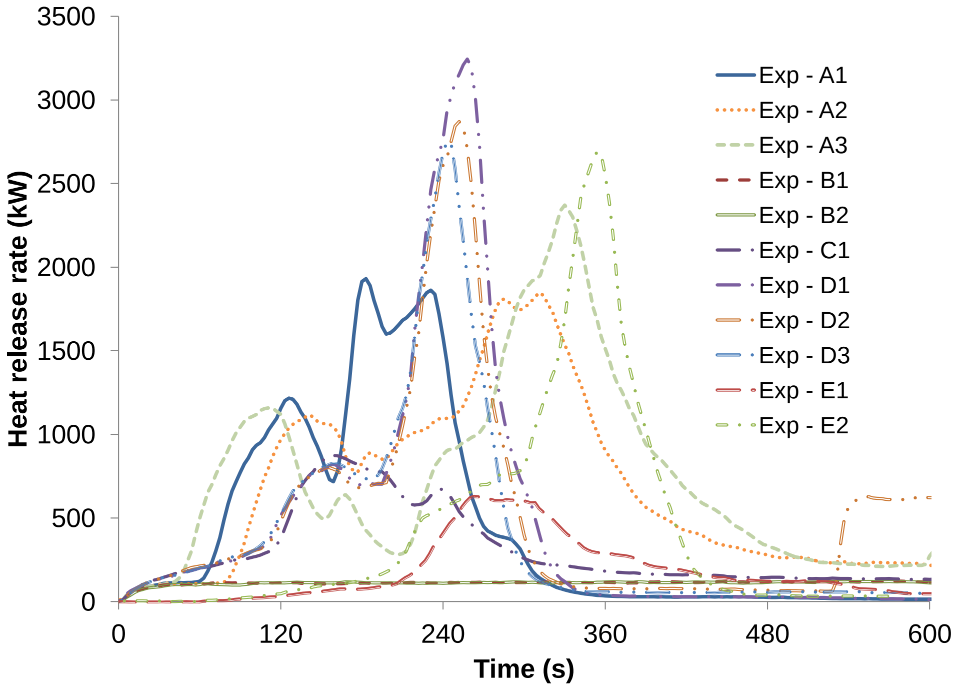


Figure 6.14: Heat release rate from the ISO 9705 compartment fire tests. Data is smoothed using a 30 s moving average filter.

sprinklers. The standard deviation was also greater, which matches the findings of Tsui et al[7].

The 3 s data acquisition time resolution added uncertainty to the temperature measurement at the time of activation, since the average sprinkler temperature increase ranged from 0.6°C per 3 s sample to 24.1°C per 3 s sample.

The variation between the activation times in different scenarios was primarily a result of the change in fire location between scenarios and the variation in HRR and ambient temperature between tests. The HRR for first 10 minutes of each experiment is shown in Figure 6.14.

The HRR for scenario A was quite variable due to the uncertainty in ignition times for the items. For scenario B, none of the items ignited so the HRR was just the burner output of approximately 100 kW. For scenario C, the burner ignited the closest armchair but no other items ignited. The three repetitions for scenario D were quite similar due to similar ignition times. Scenario E, which did not use the burner as the ignition source, showed more variation in ignition time than scenario D. Tests A1, D1, E1, and E2 were extinguished early using a manually controlled sprinkler. For the tests where additional items ignited, the major contribution in the first 10 minutes came from the armchairs and television items. The MDF cubes continued to smoulder in some cases and ignited into flaming ignition much later once the geometry changed enough to allow it to occur.

Since scenario B only included the burner heat release rate, it will be used for further analysis of the sprinkler response. Tests B1 and B2 were different from a sprinkler operation standpoint due to the difference in ambient temperature as the room was not allowed to cool completely between tests. The ambient temperature was approximately 21^{o}C for test B1 and 27^{o}C for test B2. Test B1 will be used for the further analysis presented here.

The experimental sprinkler-related data, including the sprinkler activation times, the modified sprinkler temperature response, measured ceiling jet temperature and velocity, and HRR from test B1 is shown in Figure 6.15. All of these parameters with the exception of the HRR are shown for the other tests in Appendix B. As expected, the parallel orientated sprinklers had a slower thermal response compared to the perpendicular oriented sprinklers, and also appeared to activate at a higher temperature.

6.6.2 Heskestad's model

The thermal response of the sprinklers was estimated by applying the measured ceiling jet temperature and velocity to Heskestad's model (Equation 6.1) with and without a conduction factor applied, shown in Figure 6.16. The conduction factor used was 0.44 $(m/s)^{1/2}$, which was the nominal value measured by Tsui et al[7] for a similar sprinkler. Nominal RTI values of 95 $(m\ s)^{1/2}$ and 108 $(m\ s)^{1/2}$ were used for the perpendicular and parallel orientations, respectively, as measured in the plunge test for the modified sprinklers and discussed in Section 6.5.3. While the calculated thermal response was slower than the experiment when the conduction factor was not used, it was even slower when conduction losses were added, as expected.

Using the measured ceiling jet temperature and velocity, a nominal activation temperature of 68^{o}C and the above mentioned RTI and conduction response factors, Heskestad's model predicted activation times of 111 s and 117 s for the perpendicular and parallel orientations respectively (with conduction) and 96 s and 105 s for the perpendicular and parallel orientations respectively (without conduction).

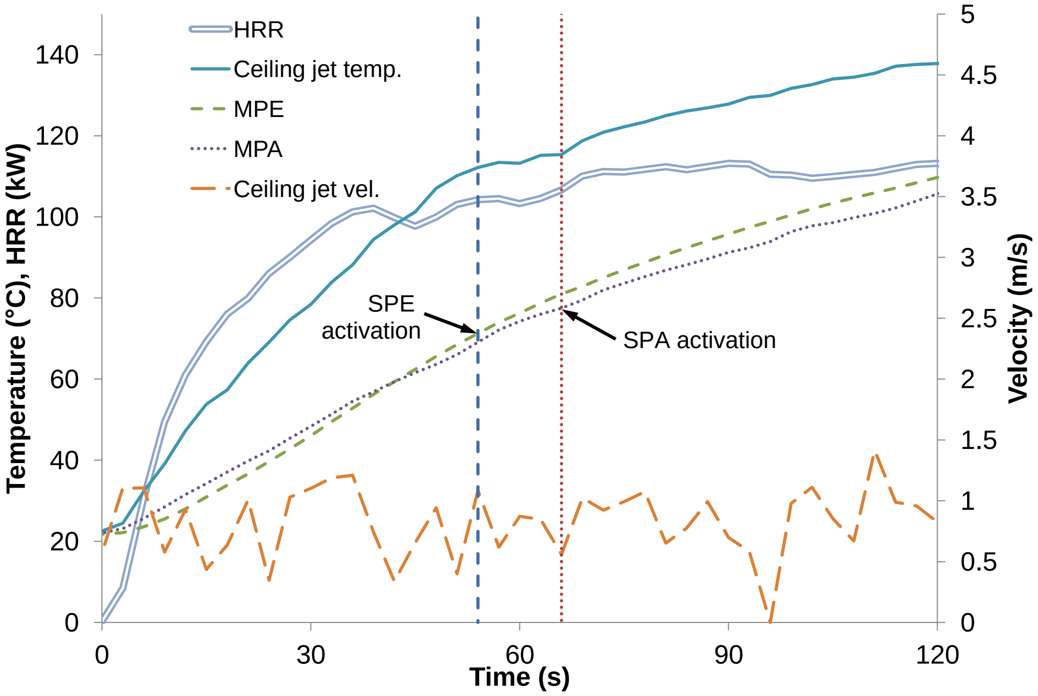
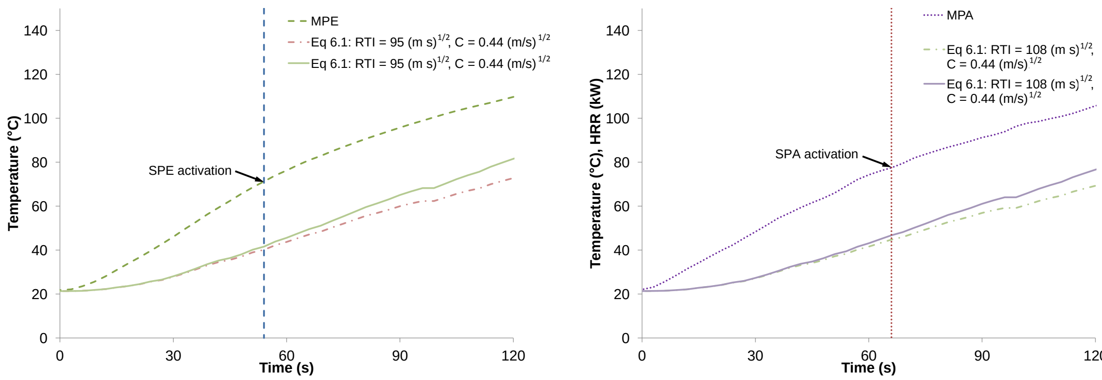


Figure 6.15: Sprinkler related data from test B1. The sprinkler activation times are shown as vertical lines with the same style as the modified sprinkler response.



(a) Perpendicular (b) Parallel

Figure 6.16: Comparison of actual sprinkler response in test B1 to Heskestad's thermal response correlation (Equation 6.1) using the measured ceiling jet temperature and velocity, with and without conduction. The experimental activation times are shown as vertical lines.

Description	Activation time (s)
Measured (SPE)	54
Eq. 6.1: C = 0 $(m/s)^{1/2}$	96
Eq. 6.1: C = 0.44 $(m/s)^{1/2}$	111
BRANZFire 2011.2	103
B-RISK 23	111
B-RISK 48	165

Table 6.2: Comparison of activation times between the perpendicular sprinkler in test B1 and thermal response models.

6.6.3 Comparison to B-RISK and BRANZFire

Comparisons of the measured ceiling jet temperature and velocity to B-RISK and BRANZFire 2011.2 model results are shown in Figures 6.17 and 6.18. For the ceiling jet temperature, two versions of B-RISK are compared; one (build 23) that used the same McCaffrey plume entrainment model as BRANZFire 2011.2 and a later version (build 48) that used Heskestad's plume entrainment model. The NIST JET model for calculating the ceiling jet temperature and velocity was used for all three zone models. Models that did not include an option to extract the output parameters were excluded in the comparison. Ceiling jet velocity measurements were not possible for the entire test duration, as the tubing connecting the bi-directional tubes to the pressure transducers failed once they melted due to the fire.

The simulated velocity was lower than the measured velocity. A contributing factor was that the bi-directional probe was located closer to the fire than the sprinkler location in the model where the ceiling jet velocity was calculated.

A comparison of the thermal response of the perpendicular sprinkler to Heskestad's model using the measured ceiling jet conditions and also B-RISK and BRANZFire output are shown in Figure 6.19. The measured HRR, nominal RTI value of 95 $(m\ s)^{1/2}$, and conduction factor of 0.44 $(m/s)^{1/2}$ were used for the B-RISK and BRANZFire simulations.

Table 6.2 compares the estimated activation times to the actual activation time. The nominal 68^{o}C activation temperature was used for all of the modelled activation times. If the measured activation temperature of approximately 72^{o}C had been used, the modelled activation times would have been slightly longer.

Most of the simulated sprinkler activation times were similar, with the exception of the B-RISK 48 value. The difference in the B-RISK 48 value was likely due

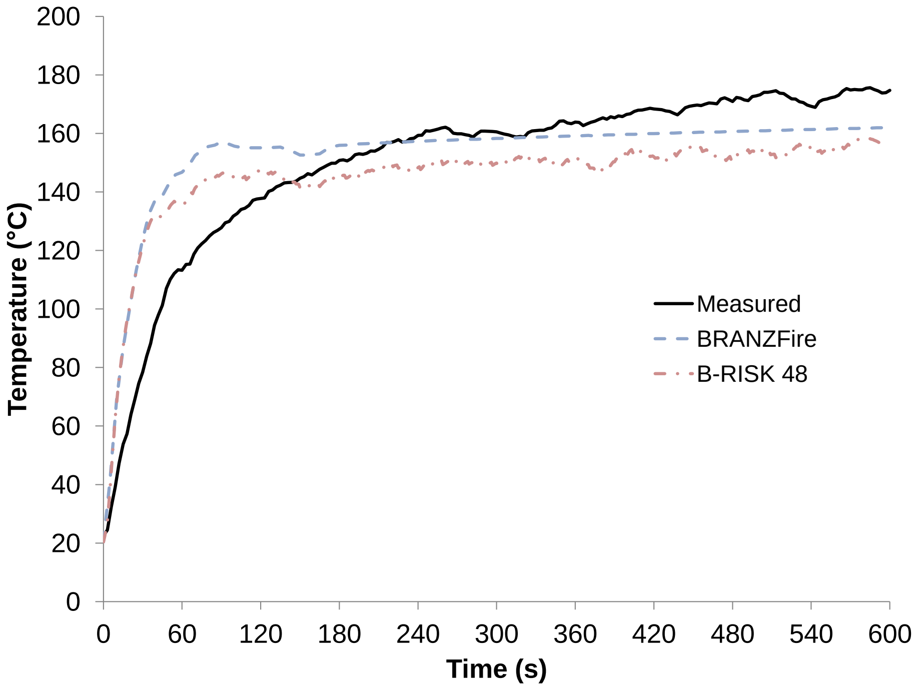


Figure 6.17: Comparison of the BRANZFire, B-RISK 23 (McCaffrey plume entrainment model), and B-RISK 48 (Heskestad plume entrainment model) estimated ceiling jet temperature with the measured value from test B1.

to the difference in the predicted upper layer temperature and layer height, which are used in the NIST JET model to predict the ceiling jet properties. Plots of the predicted layer heights and upper layer temperature for the three models are shown in Figure 6.20.

The layer properties in the B-RISK 48 simulation started to diverge from the BRANZFire and B-RISK 23 values at approximately 45 s, prior to the ceiling jet temperature divergence.

6.6.4 Radiation factor

To try to account for the difference between the observed and simulated sprinkler thermal response, the radiation factor proposed by Sako and Hasemi was added. The contribution of the upper layer was neglected. The external radiation flux $\dot{q}_e''$ was estimated as the radiation from the flame added to the radiation from the compartment surfaces:

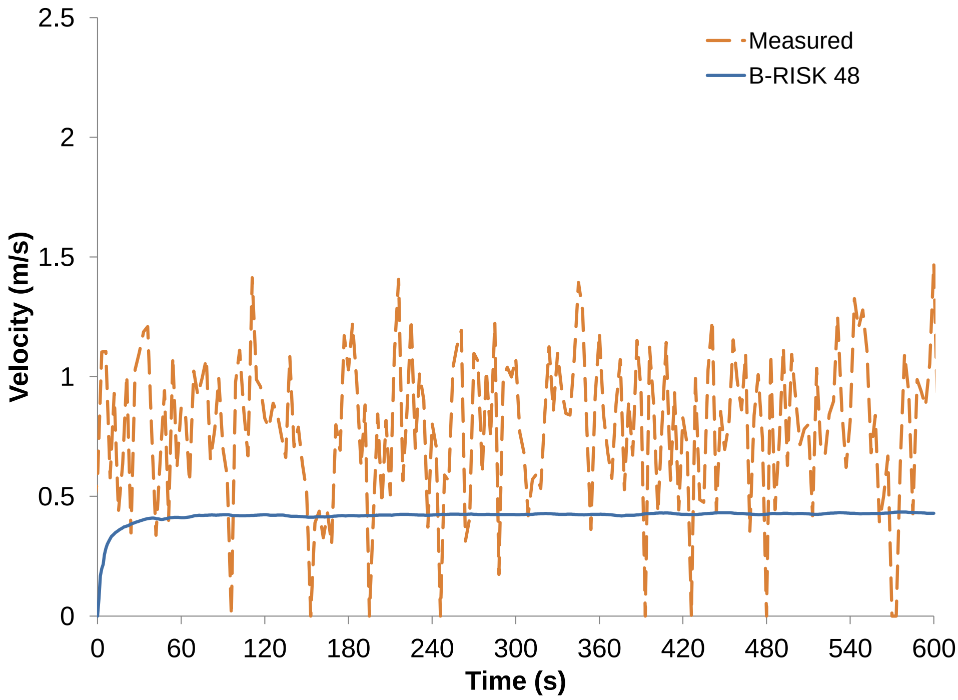


Figure 6.18: Comparison of the B-RISK 48 (Heskestad plume entrainment model) ceiling jet velocity prediction with the measured value from test B1.

$$\dot{q}_e'' = \chi_{rad} Q F_{flame-d} + \sigma T^4_{surroundings} \tag{6.5}$$

where χ_{rad} is the radiative loss fraction, Q is the total HRR of the fire, and $F_{flame-d}$ is the view factor from the flame to the detector element. The $\sigma T^4_{surroundings}$ term represented the radiation incident on the detector from the compartment, assuming a view factor of approximately unity. It was assumed that the compartment temperature was approximately equal to ambient for the initial stages of the fire before the sprinklers activated.

The flame was assumed to be a cylindrical surface from the top of the burner to the ceiling. The view factor $F_{flame-d}$ was calculated to be 0.014 for the compartment geometry using the relation for a cylinder to a parallel surface (Figure 6.21) found in the SFPE handbook[14]:

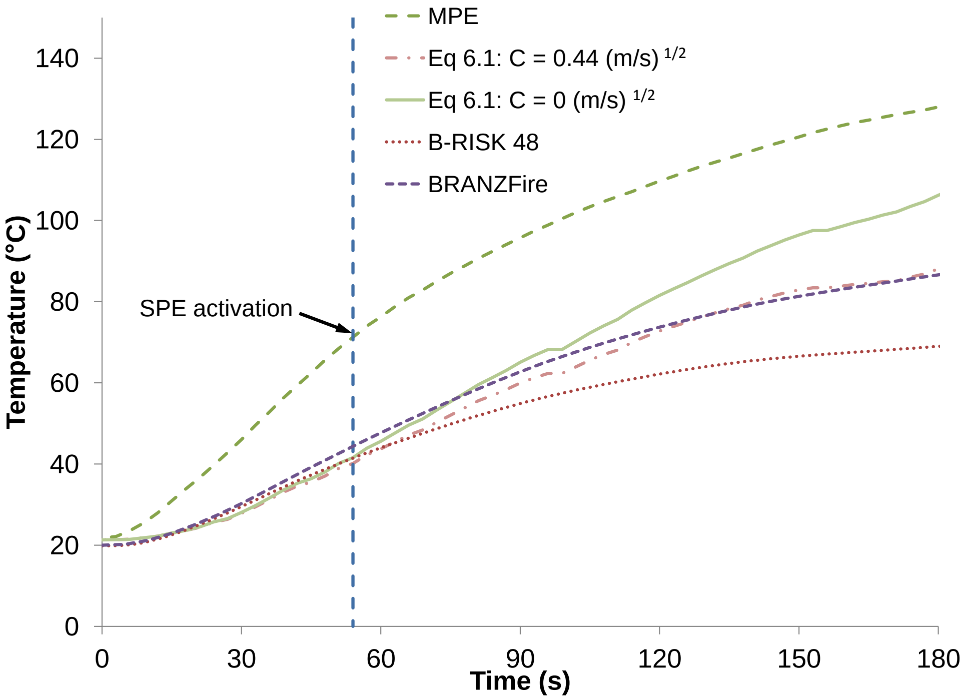
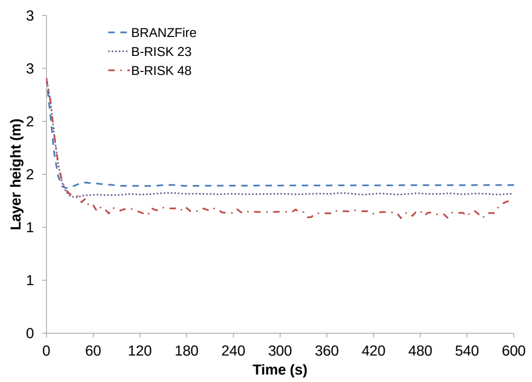
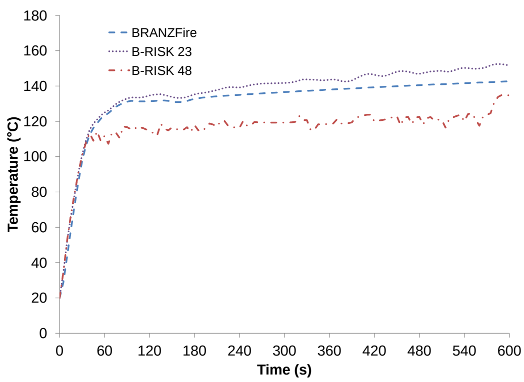


Figure 6.19: A comparison of the measured perpendicular sprinkler thermal response with the output from B-RISK 48 (Heskestad plume entrainment model) and BRANZ-Fire 2011.2 and the predicted thermal response using the Heskestad thermal response model using the measured ceiling jet temperature and velocity.



(a) Layer height



(b) Upper layer temperature

Figure 6.20: Comparison of the layer height and temperature between BRANZFire 2011.2, B-RISK 23, and B-RISK 48.

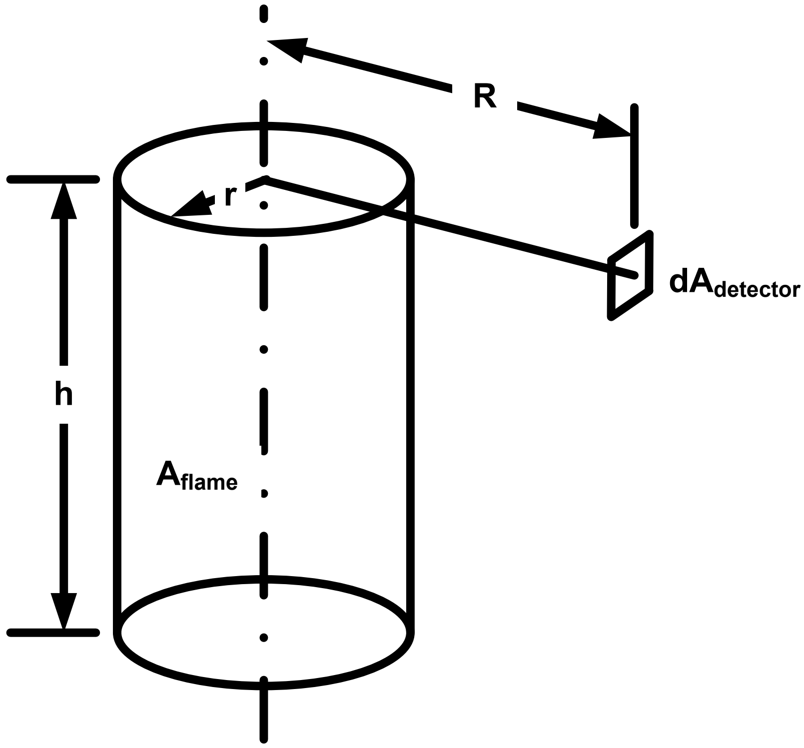


Figure 6.21: The view factor for a cylindrical surface to a perpendicular differential area was used to estimate the radiation reaching the sprinkler bulb from the flame. For scenario B, the dimensions are r = 0.085 m, R = 2.4 m, and L = 2.1 m.

$$\begin{aligned}
L &= \tfrac{h}{r}; H = \tfrac{R}{r} \\
X &= (1+H)^2 + L^2; Y = (1-H)^2 - L^2 \\
F_{dA_{detector}-A_{flame}} &= \tfrac{1}{\pi H} tan^{-1}\left(\tfrac{L}{\sqrt{H^2-1}}\right) + ... \\
\tfrac{L}{\pi}&\left[\tfrac{X-2H}{H\sqrt{XY}} tan^{-1}\sqrt{\tfrac{X(H-1)}{Y(H+1}} - \tfrac{1}{H} tan^{-1}\sqrt{\tfrac{H-1}{H+1}}\right]
\end{aligned} \tag{6.6}$$

The results of adding the radiation term to Heskestad's thermal response model are shown in Figure 6.22. Using the C_r obtained by Sako and Hasemi[10] of 0.21 $\frac{Km^2}{kJ}$ was not sufficient to increase the temperature response to the level measured by the modified sprinklers. A closer match was obtained by increasing the C_r value by an order of magnitude to 2 $\frac{Km^2}{kJ}$; however, more testing is required to determine if this is a reasonable value for glass bulb type sprinklers. This could be done with a cone type heater to subject a glass bulb sprinkler to radiation as described by Sako and Hasemi[10].

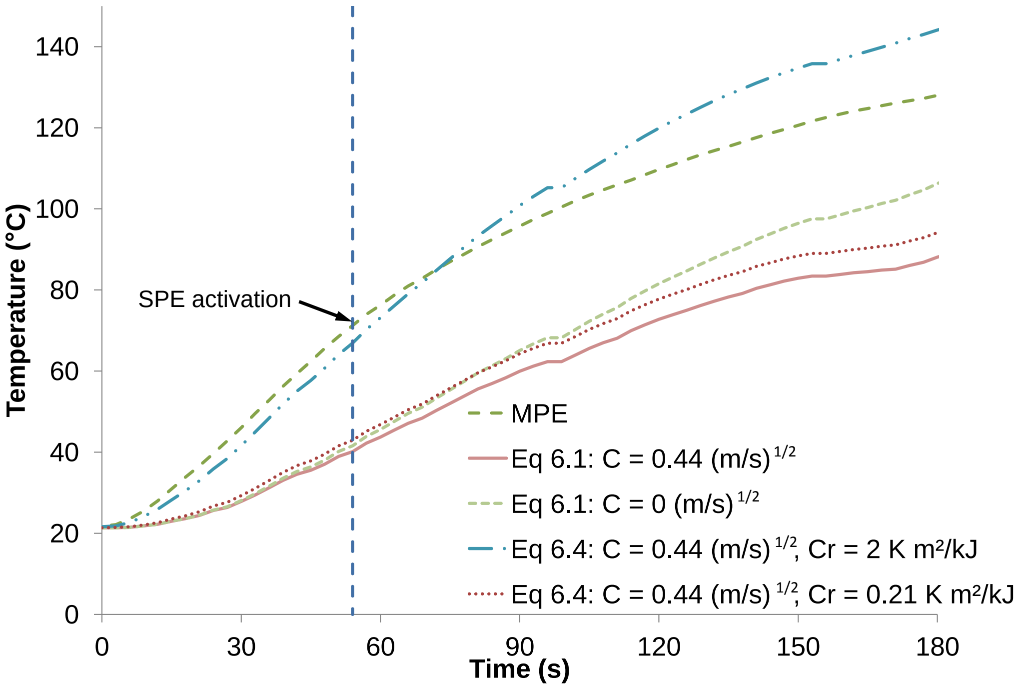


Figure 6.22: The results of adding the radiation term to Heskestad's model. A C_r value of approximately 2 $\frac{Km^2}{kJ}$ was required to approximate the measured response. The vertical line represents the activation time of the standard sprinkler.

6.7 Conclusions

The ability of modified sprinklers with thermocouples inserted in custom sprinkler bulbs to provide a representation of the response of a glass bulb sprinkler was investigated. While parallel orientations did increase the RTI measured in the plunge test, it did not increase enough to completely explain the increased activation times for standard sprinklers measured by Tsui et al[7]. The side-by-side comparison of the temperature of the modified sprinklers at activation of standard sprinklers in the compartment tests indicates that the parallel orientation also increases the activation temperature of the sprinkler bulbs.

The addition of water in the plunge tests did not seem to significantly affect the thermal response under the conditions tested, although it may become more of a factor for lower gas temperatures or velocities.

The Heskestad plume entrainment model used in the latest version of B-RISK appears to predict slower thermal response than the models using the McCaffrey plume entrainment model. Sprinkler response times calculated with the computer models using the McCaffrey plume entrainment model were closer to the activation times calculated using measured ceiling jet properties in Heskestad's thermal response model.

Radiation in the ISO 9705 compartment fire test conditions appears to be a significant source of heating relative to convection from the ceiling jet for the sprinkler thermal response. Further testing of the sprinkler temperature response with a radiative source such as a cone heater would be useful to characterise the C_r parameter for a standard response glass bulb sprinkler. Preferably, a modified sprinkler would be compared side-by-side with a standard response bulb for the radiative heating tests in a similar fashion to that used for the ISO compartment fire tests.

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Chapter 7

Uncertainty in Sprinkler System Effects on the Fire After Activation

7.1 Introduction

An NFPA sprinkler effectiveness study[1] of actual sprinkler performance in fire incidents has indicated that effectiveness decreases as the number of sprinklers activated increases. Deterministic design approaches do not allow a comparison between the number of sprinklers expected to operate in a design and what has been observed in statistical analysis of actual fire incidents. The trend of water supply authorities to reduce reticulation system water pressure has been noted as a potential to decrease effectiveness of sprinkler systems and increase fire risk, but current design methods do not allow for the quantitative consideration of these effects.

Water is a finite resource and while it is extremely effective as an agent for both manual and automatic fire suppression activities, it has many other important uses; many arguably more important than fire protection. Clean, potable water is essential for modern public health and large quantities of water are also necessary to support the modern agricultural practices required to feed the population of the world. Pollution, climate change, and increases in societal usage put pressure on the water cycle. Ageing municipal water distribution systems contribute to the problem as they deteriorate and start to leak and rupture at greater rates. All of these factors add up to greater costs for municipalities to provide clean water, which are of course ultimately borne by the taxpayer. In New Zealand and elsewhere in the world, municipal water suppliers have been searching for methods to reduce their water losses and also to increase the reliability of their reticulation systems in a cost effective manner. One of the methods that is starting to see widespread use in New Zealand is pressure reduction.

It has been estimated that 90% or more of the approximately 7000 sprinkler systems installed in New Zealand are reliant on towns' mains water supplies[2]. The New Zealand fire protection industry has voiced concerns that reduced pressure in the water distribution system will cause sprinkler systems that were designed to be compliant with national and international standards to fall out of compliance and create unforeseen property and life safety fire risks that these sprinkler systems were designed to mitigate.

An example of mains pressure reduction was planned in Christchurch, late 2012. The council intended to rezone the water reticulation system from seven zones to fourteen to allow more effective pressure management. A result of the change was that 400 kPa would be the maximum street main pressure available for sprinkler systems[3]. A local fire safety contractor indicated that existing buildings in the city centre were designed for a street main pressure of 750 kPa[4]. The contractor estimated that many existing buildings would require an additional booster pump, with a capital cost of approximately $75,000, annual maintenance of $3,000, and using 10 m^2 of ground floor area.

The foreword to sprinkler standard NZS 4541:2007[5] acknowledges these issues. It is unclear who is responsible to remedy this potential problem and who could be liable for excess damage during fires due to ineffective sprinkler systems because of low water supply pressure. This chapter examines the basis for these concerns and discusses the potential effects that town's mains water reticulation pressure reduction could have on sprinkler systems in New Zealand. Extra light hazard (ELH) and ordinary hazard (OH) wet pipe sprinkler systems designed under the NZS4541:2007 standard using standard spray sprinklers as described in NZS4541:2007 section 402.2.1 (b) will be considered.

A new risk-informed fire engineering design tool that allows the explicit consideration of uncertainty is currently under development in New Zealand. This chapter describes how the new model considers the effects of sprinkler systems on fire development, and the ability of the model to predict multiple sprinkler activations.

7.2 Sprinkler modelling in B-RISK

Due to the design fire generator's probabilistic placement and selection of the first item ignited, all of the sprinklers in the compartment of fire origin are modelled and the activation of multiple sprinklers can be estimated. Currently, there are no limitations on the number of sprinklers that can be placed in the model.

7.2.1 Modelling sprinkler effects on heat release rate in B-RISK

Four options can be selected to incorporate the effect of the sprinklers on the heat release rate of the fire, as shown in Figure 7.1. The sprinklers can be assumed to have no effect on the heat release rate, as would be the case if there was no water supplied to the sprinklers. The second option assumes that the sprinklers control the fire; i.e. the heat release rate remains constant after the first sprinkler is activated for the remainder of the simulation. This is the approach taken in the newly proposed Verification Method for fire safety C/VM2 in New Zealand[6]. The fire risk model FIERAsystem developed in Canada uses a similar approach, but also includes a sprinkler effectiveness parameter that allows the fire to continue to grow after the activation of the first sprinkler is predicted[7]. The C/VM2 style control option is used if the design fire generator is not active. A second control option allows for the ignited items to burn out once the combined heat release rate curve is calculated to have dropped below the control threshold, and is used in conjunction with the design fire generator. The fourth option uses a modified version of the suppression algorithm introduced by Evans[8] for unshielded furnishing fires. The original version was developed for experiments with constant water spray density where the sprinklers are assumed to cause the heat release to decay exponentially as described by the following formula:

$$Q_{t-t_{act}} = Q_{t_{act}} e^{-\frac{t-t_act}{3.0w"^{-1.85}}} \qquad (7.1)$$

where t is the time, t_{act} is the time of the first sprinkler activation, Q is the heat release rate in kW, and w" is the nominal water spray density in mm/s. This is an exponential decay model that assumes that the effect of the sprinklers on the fire is proportional to the heat release rate of the fire:

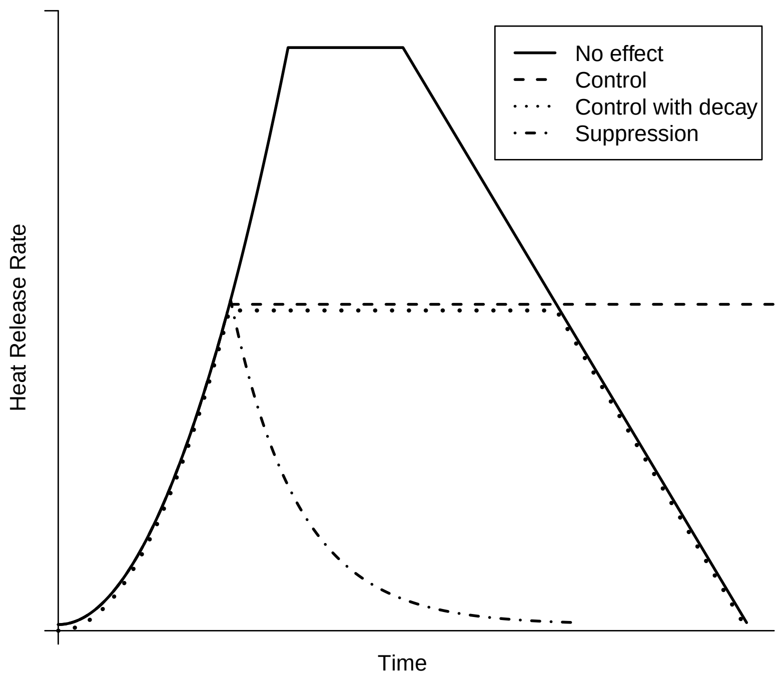

Figure 7.1: Options for the sprinkler effect on fire heat release rate in B-RISK.

$$\frac{\partial Q}{\partial t} = \lambda Q \tag{7.2}$$

Rearranging Equation 7.2 to separate the variables of Q and t results in the following form:

$$\frac{\partial Q}{Q} = \lambda \partial t \tag{7.3}$$

Integrating both sides from t_{act} to t

$$\int_{Q_{t_{act}}}^{Q} \frac{dQ}{Q} = \int_{t_{act}}^{t} \lambda dt \tag{7.4}$$

$$ln(Q) = \int_{t_{act}}^{t} \lambda dt + ln(Q_{t_{act}}) \tag{7.5}$$

and raising the equation to the exponent yields

$$Q = Q_{t_{act}} e^{\int_{t_{act}}^{t} \lambda dt} \tag{7.6}$$

If λ is constant with time then

$$Q = Q_{t_{act}} e^{\lambda(t - t_{act})} \tag{7.7}$$

which is the form used by Evans with

$$\lambda = \frac{1}{2.0x10^{-5}(w"/H_c)^{-1.85}} \tag{7.8}$$

as the time constant, fit as an upper bound to experimental sprinkler suppression data from wood crib fires, where H_c was the height of the crib. It should be noted that the data considered included 305 mm and 610 mm tall wood cribs and should be used with caution for fuel packages that are significantly different in configuration, such as high challenge fuel packages. Using 610 mm as a nominal height for most furnishing fires results in the form used in B-RISK:

$$\lambda = \frac{1}{3.0w"^{-1.85}} \tag{7.9}$$

When considering successive sprinkler activation, the water spray density typically does not remain constant throughout sprinkler operation. As additional sprinklers activate, the total flow increases but the flow from each sprinkler decreases due to the increased friction losses in the hydraulic system, and therefore the minimum spray density also decreases, as shown in Figure 7.2.

Substituting the above function into the time integral in Equation 7.6 gives

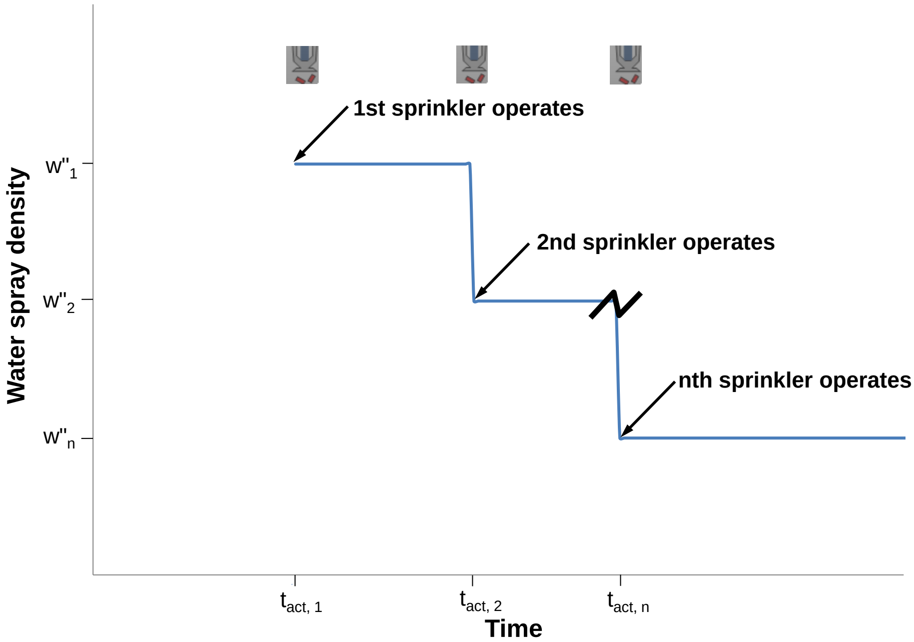

Figure 7.2: As additional sprinklers activate, the water spray density decreases.

$$Q = Q_{t_{act,1}} e^{-\frac{1}{3.0}\sum_{i=1}^{n}\frac{(t_{i+1}-t_{act,i})}{w_i"^{-1.85}}} \tag{7.10}$$

where n is the number of activated sprinklers, $t_{act,i}$ is the activation time of the ith sprinkler, $w"_i$ is the minimum water spray density after the ith sprinkler activates, and t_{i+1} is equal to the activation time of the $(i+1)$th sprinkler if $i+1 \leq n$ and t if $i+1 > n$. An increase in spray density due to overlapping spray from adjacent operating sprinklers is not considered.

7.2.2 Probabilistic inputs for sprinkler system effectiveness

A probabilistic input is included in the model representing the probability that the sprinkler system has an effect on the fire growth. This outcome would be expected if water is available for the system; for example, as long as the water supply was not compromised or an isolation valve was not shut off. This parameter corresponds

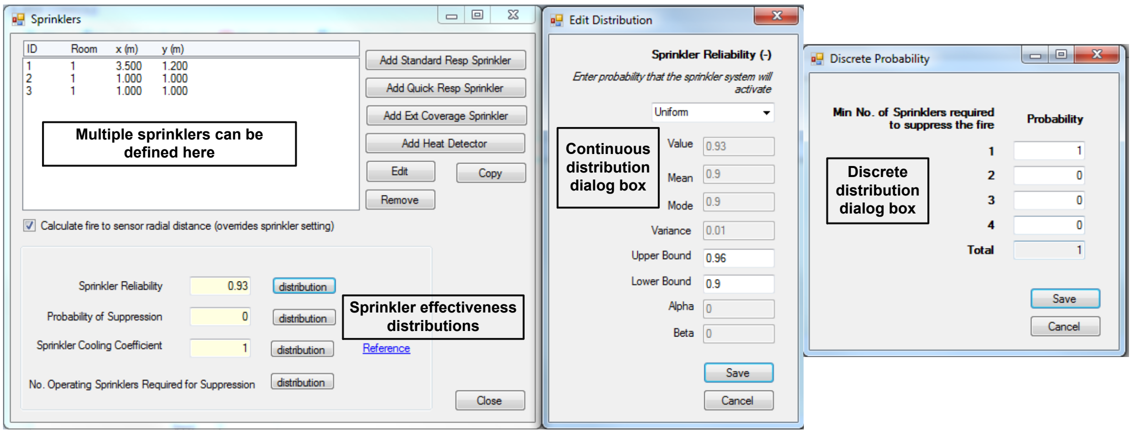

Figure 7.3: B-RISK forms for entering sprinkler system effectiveness distributions. Multiple sprinklers can be entered, with distributions for suppression, control, and no effect probabilities.

to the probability that the sprinkler system is reliable. If the sprinkler system is assumed to have an effect on fire growth, a second distribution can be used to select how many sprinklers are activated before the fire growth is modified, creating an effect similar to the FIERAsystem approach. The effect is also similar to the approach discussed in the IFEG[9] of increasing the radial distance input into the model if a more conservative estimate of sprinkler activation is required. A third distribution can then be used to estimate the probability whether the system controls or suppresses the fire if the system activates and sufficient water is available. This parameter is representative of the probability of sprinkler system efficacy. The B-RISK input windows for these distributions are shown in Figure 7.3.

7.2.3 Modelling the activation of subsequent sprinklers in B-RISK

B-RISK makes a number of assumptions in estimating the activation of subsequent sprinklers. It has been observed that sprinkler sprays interact with the fire plume[10], and there have been models developed to consider these effects[11], Sprinklers also interact with the upper smoke layer[12], and it has been noted that water from activated sprinklers can prevent other sprinklers from activating[13,14]. An equation has been developed for thermal detector response that includes evaporative cooling[15], but there is insufficient data to predict how much water from activated sprinklers reaches sprinklers not yet activated. There is also evidence that water spray from sprinklers affects fire-driven vent flows[16]. The present risk-informed model does not account for any of these effects; however, they are all expected to reduce the temperature of gases reaching other sprinklers or to otherwise cool them. Thus, the assumption made to exclude these effects is expected to result in over predicting the number of sprinklers activated, creating an "upper bound" estimation which may be useful for evaluating the hydraulic adequacy of water supplies for risk purposes. It should be noted that the model is unable to predict the activation of sprinklers outside the room of fire origin and this may cause the model prediction to not be conservative depending on the situation being modelled. A major contributing factor to estimating when subsequent sprinklers activate is accurately estimating the effect of activated sprinklers on the heat release rate, for which data is very limited. To evaluate the contribution of these effects, a comparison is made in Section 7.4 between one set of data and the model prediction.

7.3 Modelling sprinkler water supplies in B-RISK

To estimate the effects of water supply pressure and flow fluctuations on the fire risk in a sprinklered building, the sprinkler system hydraulic characteristics are required. A hydraulic model that calculates the flow and pressure at activated sprinklers was developed and integrated with the B-RISK multiple sprinkler activation and sprinkler heat release rate submodels. A description of the hydraulic model development and capabilities is included in Appendix A. The hydraulic model in B-RISK assumes steady state water flow in the piping, neglecting transient flow phenomena.

Sprinkler water spray density is calculated in the hydraulic model by dividing the sprinkler flow by the coverage area specified for the sprinkler. Individual coverage areas can be specified for each sprinkler. The minimum water spray density and sprinkler pressure at a single sprinkler is calculated after each sprinkler activation. The minimum water spray density after each sprinkler activation is used in the suppression model to modify the heat release rate.

Below a critical sprinkler spray density or pressure, the sprinkler system will cease to effectively control or suppress the fire as the full spray pattern degrades to a drizzle. The critical density and pressure can be entered in the model. Depending on the level of conservatism required, the heat release rate can either be specified to be held constant after the minimum flow drops below the critical quantities or can be specified to resume growing. Estimates of the critical values can be obtained from sprinkler standards. These values may be conservative but no data has been found to support the decrease in sprinkler system efficacy at flow characteristics below standard specified values. New Zealand sprinkler standard flow requirements are discussed below.

7.3.1 NZS4541:2007 water supply requirements

The NZS4541:2007 sprinkler standard provides minimum design flow and pressure requirements for sprinkler systems. These minimum criteria may be used as the critical cutoff for effective sprinkler operation in the hydraulic model.

7.3.1.1 NZS4541:2007 minimum sprinkler flow requirements

Minimum sprinkler flow rates can be calculated by multiplying the coverage area for an individual sprinkler by the minimum design water spray density for the occupancy and hazard. Design densities specified in NZS4541:2007 range from 4.1 mm/min for the extra light hazard classification to 12.5 mm/min or more for process occupancies.

7.3.1.2 NZS4541:2007 minimum sprinkler pressure requirements

NZS4541:2007 specifies in Section 1002.3.1 that the minimum orifice *"pressure at any sprinkler, with all sprinklers within the assumed maximum area of operation simultaneously operating, shall not be less than:*

- *In extra light hazard occupancy class:*
  - *using 10 mm sprinklers - 100 kPa*
  - *using 15 mm sprinklers - 50 kPa*
  - *using residential sprinklers - as per the listing*

- *In ordinary hazard occupancy class - 50 kPa*
- *In extra high hazard occupancy class - 50 kPa"*

Other criteria are also given for control mode specific application and supression mode sprinklers, but these sprinkler types will not be considered in this study. The effect of the sprinkler system on the fire once the flow no longer meets the minimum critical requirement can be set to either no effect or control.

7.4 Comparison to Ghent sprinkler tests

Experimental data in the literature where multiple sprinkler activation times and heat release rate histories before and after sprinkler activation have occurred is limited. One set of experiments that included sprinkler activation times and a quantifiable heat release rate with activated sprinklers was conducted by the UK Building Research Establishment at the Multifunctioneel Trainingcentrum in Ghent, Belgium[17]. While these experiments were focused on the interactions of sprinklers and smoke vents, two tests were conducted with no vents open, which were used for comparison to B-RISK simulations.

7.4.1 Description of experiments

The building space where the sprinklers were tested was approximately 50 m long, 20 m wide, and 10 m tall. A 3.2 m smoke curtain created a 27 m long by 18 m wide smoke reservoir with a flat ceiling. The experiments used for this comparison had 55 sprinklers in a grid as shown in Figure 7.4. A 1.8 m radius dodecagonal pan filled with water and hexane piped into the centre was used as a growing fire source. A relation between the amount of hexane pumped into the pan and the surface area of the hexane as it spread across the water was developed so a controlled growing fire source could be created. A steel upstand 20 cm high around the pan was used to prevent splashing by the sprinkler water discharge.

Wormald Type A 15 mm upright spray sprinklers were used for these experiments, with a nominal operating temperature of 68°C, and mounted 150 mm below the ceiling. However, the experimental report indicated that the best match between a zone model developed by Hinkley (which used Alpert's correlation for the ceiling jet temperature and velocity[18]) and the experimentally measured activation time was obtained by using an operating temperature of 80^{o}C. The time constant for these sprinklers was measured at 1 m/s and was 200 s for perpendicular flow to the yoke arms and 370 s for parallel flow to the yoke arms. The report stated that the yoke arms of the installed sprinklers were oriented to be perpendicular to the central fire location. The response time index (RTI) required by the model was calculated by multiplying the time constant by the square root of the test velocity, as described by Heskestad and Bill[19], to get RTI values of 200 (m s)$^{1/2}$ and 370 (m s)$^{1/2}$.

The hexane was added to the pan at an exponentially increasing rate to produce the heat release curve comparable to an ultra-fast t^2 fire shown in Figure 7.5. At the time of ignition the amount of hexane added corresponded to a heat release rate of 830 kW, and the size of the pan allowed for a maximum of 14 MW. For the two experiments (experiments 25 and 26) where no vents were used, the heat release rate was modified using two approaches. For experiment 25, the heat release rate was held constant after the first sprinkler activated. In this experiment, all 55 sprinklers activated.

For experiment 26, the heat release rate was held constant after the first sprinkler activated and then reduced by 20% after 30 s. In this experiment, 36 sprinklers activated. A comparison of the modelled and experimental sprinkler activation times are shown in Figures 7.6 and 7.7. Sprinkler activation times greater than 400 s were not reported from the experiments.

7.4.2 Model inputs

Since sprinkler activation times greater than 400 s were not reported from the experiments, 400 s was used as the simulation run time. Based on guidance from the experimental report, a heat release radiative fraction of 0.39 was used. The JET model was used to model the ceiling jet temperature and velocity based on the recommendations of Wade et al[20]. Due to the recommendations in the experimental report, two RTI and activation temperature combinations were modelled, discussed in the results below. A typical conduction factor of 0.4 (m/s)$^{1/2}$ was used. The distance of the sprinkler heads from the ceiling was modelled as 150 mm, equivalent to the experiments. B-RISK release version 17 was used for this analysis.

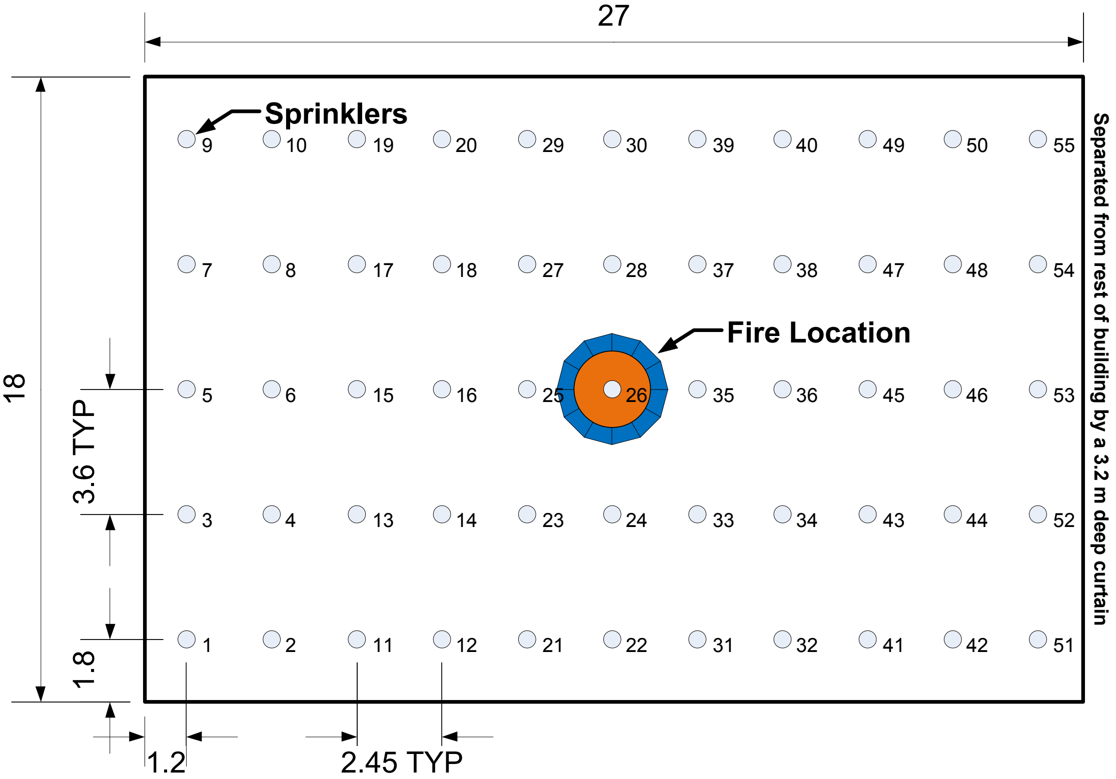

Figure 7.4: Ghent experimental layout[17]. Ceiling height was 10 m. Original sprinkler numbering scheme shown. Dimensions are in metres unless otherwise stated.

7.4.3 Model results

The activation time of the first sprinkler can be used to evaluate the ability of the model to predict the sprinkler bulb response when there are no effects of the sprinkler spray on the fire plume, upper layer, and unactivated sprinkler bulbs. The model predicted the first sprinkler activation time to be 146 s using a RTI of 350 (m s)$^{1/2}$ and an activation temperature of 80^{o}C, compared to the experimental value of 146 s (0% difference) for experiment 25 and 150 s for experiment 26 (3% difference). Since a growing fire was used as the source, and the heat release rate was controlled when the first sprinkler activated, the modelled time of sprinkler activation affected the heat release rate history.

When the activation temperature was changed to the nominal value of 68^{o}C reported for the actual sprinklers installed, and the RTI was changed to 200 (m s)$^{1/2}$ as measured with the yoke arms perpendicular to the flow (as they were installed), the first sprinkler was predicted to activate at 102 s (32% earlier) with a correspond-

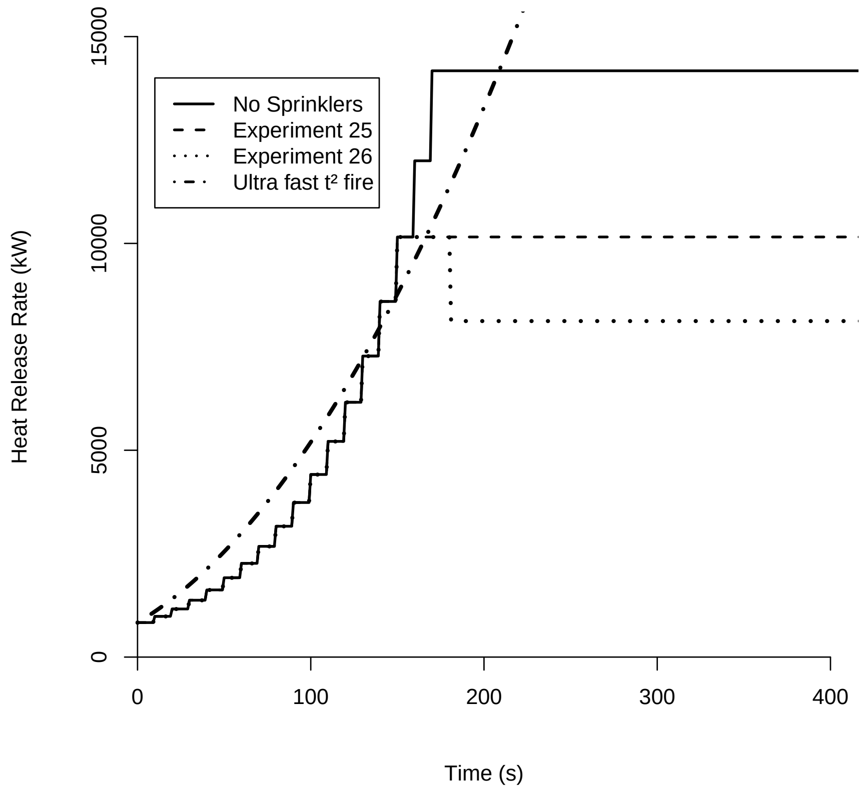

Figure 7.5: Heat release rate curves for the Ghent growing fires[17].

ing lower heat release rate. Since the predicted activation time was much closer with the RTI of 350 (m s)$^{1/2}$ and activation temperature of 80^{o}C, these values were considered to be the ″apparent″ values, contrasted with the ″nominal″ values for RTI of 200 (m s)$^{1/2}$ and activation temperature of 68^{o}C.

For the model based on experiment 25, using a RTI of 200 (m s)$^{1/2}$ and an activation temperature of 68^{o}C for all of the sprinklers resulted in the modelled times of sprinkler activation varying from -60% to 14%, as shown in Figure 7.6. Using a RTI of 350 (m s)$^{1/2}$ and an activation temperature of 80^{o}C for all of the sprinklers, the time of activation for the subsequent sprinklers predicted by the model varied from the experimental times by -47% to 30%.

For experiment 26, the times predicted for subsequent sprinkler activations varied from -60% to 12% when a RTI of 200 (m s)$^{1/2}$ and activation temperature of 68^{o}C were used, as shown in Figure 7.7, and from -45% to 38% when a RTI of 350 (m s)$^{1/2}$ and activation temperature of 80^{o}C were used.

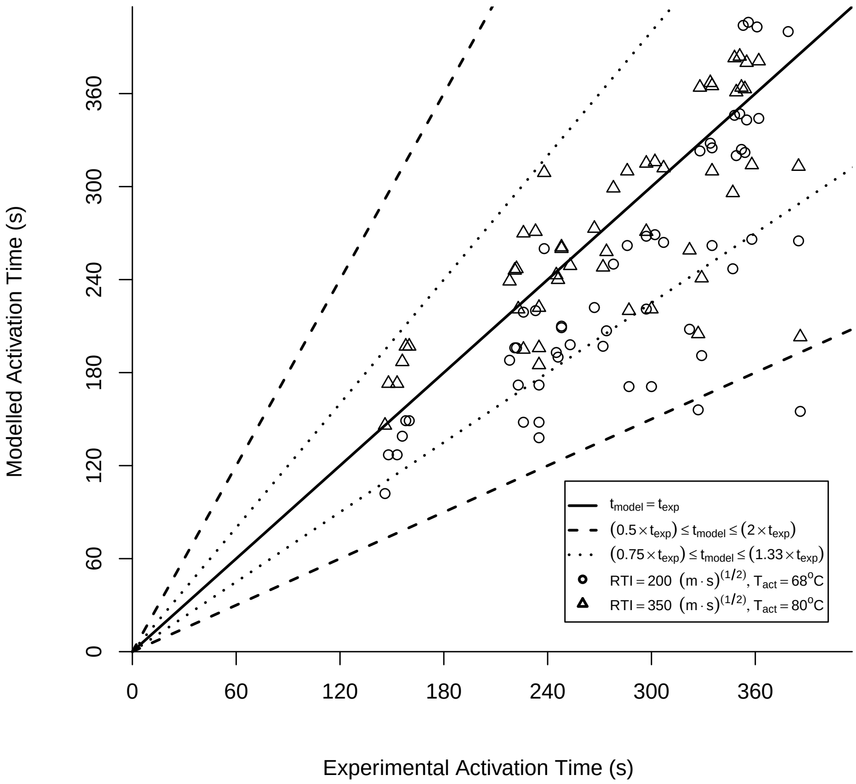

Figure 7.6: Comparison between experimental and modelled activation times for experiment 25.

Figures 7.8 and 7.9 directly compare the model error for the two cases of RTI and activation temperature modelled for experiments 25 and 26, respectively. For both experiments, a RTI of 200 (m s)$^{1/2}$ and activation temperature of 68^{o}C tended to result in an early model prediction (negative error).

Comparisons between the order of sprinkler operation can be seen in Figures 7.10 and 7.11. The concentric circles for each sprinkler can be used to visually compare the modelled activation order (centre circles) with the experimental order (outer circles). A darker shade indicates earlier activation. No shading indicates a sprinkler that does not activate. For experiment 25, the model predicted that all 55 sprinklers would activate, as happened in the experiment. For experiment 26, the model predicted that 41 sprinklers would activate compared to the 36 that activated in the experiment. This over prediction is likely due to the inability of the model to account for evaporative cooling, which in the experiment caused sprinklers 12,

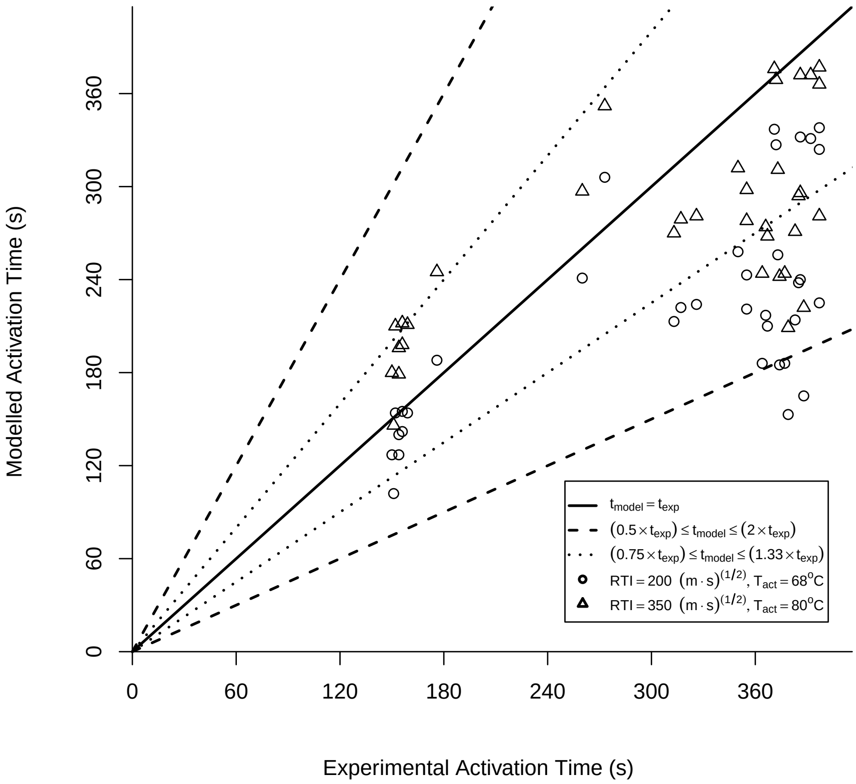

Figure 7.7: Comparison between experimental and modelled activation times for experiment 26.

32, 36, 44, and 46 to experience residual skipping (as defined by Croce et al[13] to be sprinklers that do not operate during the fire) or otherwise not activate. Sprinkler number 10 activated in the experiment, although the model predicted that it would not. It can also be seen that sprinklers 16, 37, and 38 experienced temporary skipping (as defined by Croce et al[13] to be sprinklers that operate after neighbouring sprinklers that are more distant from the plume) in the experiment, which was not predicted by the model.

Table 7.1 summarises the number of sprinklers predicted by the model to activate within 50%, 25%, and 10% of the experimental activation times for the two parameter sets tested. More sprinklers were predicted to activate within the specified uncertainty bounds for Experiment 25 compared with Experiment 26. This may be caused by the greater relative importance of the sprinkler spray effects on the plume compared with the weaker plume in Experiment 26 due to the lower

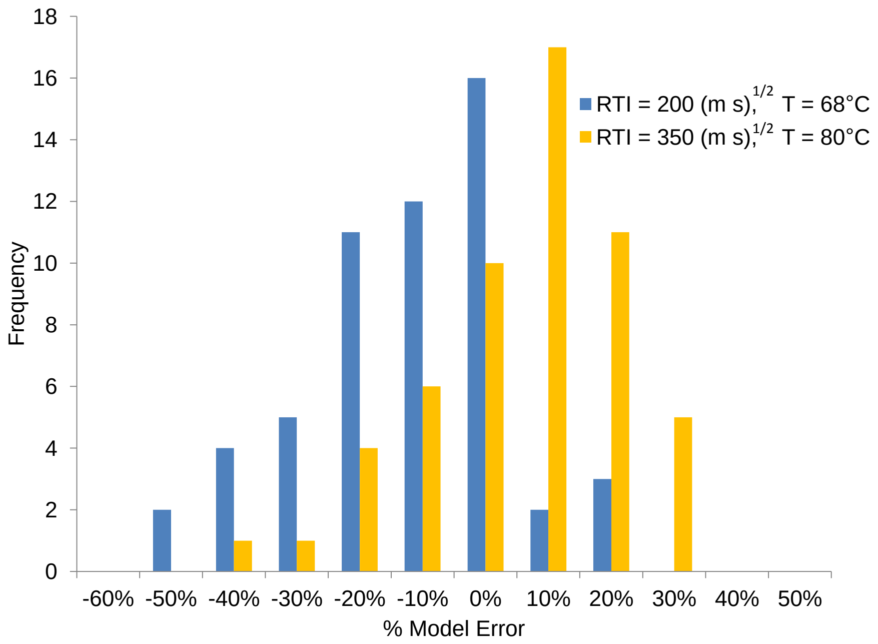

Figure 7.8: Histogram of model error for experiment 25.

Deviation From Exp. Activation Time	Experiment 25 Parameter Set #1	Experiment 25 Parameter Set #2	Experiment 26 Parameter Set #1	Experiment 26 Parameter Set #2
50%	96%	100%	89%	100%
25%	71%	91%	46%	54%
10%	33%	49%	23%	20%

Table 7.1: Percent of sprinkler activations calculated by the model within the stated deviation limits from the experimental sprinkler activation times. (Parameter set #1: RTI = 200 (m s)$^{1/2}$, T_{act} = 68^{o}C; Parameter set #2: RTI = 350 (m s)$^{1/2}$, T_{act} = 80^{o}C)

heat release rate. For both experiments, using a RTI of 350 (m s)$^{1/2}$ and an activation temperature of 80^{o}C resulted in more sprinklers predicted to activate within the specified uncertainty bounds in Table 7.1 compared with a RTI of 200 (m s)$^{1/2}$ and an activation temperature of 68^{o}C.

However, the number of sprinklers reported activated by the model remained the same, with all sprinklers predicted activated for experiment 25 and with the total number of 41 sprinklers predicted activated for experiment 26.

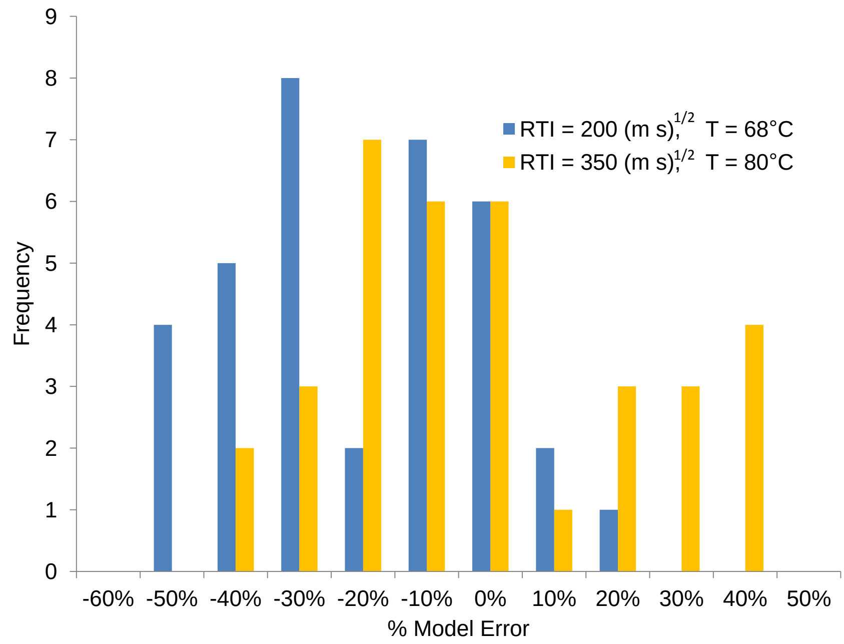

Figure 7.9: Histogram of model error for experiment 26.

7.5 Modelling water supply effects on sprinkler system effectiveness

A generic compartment representing a typical commercial occupancy protected by an extra light hazard sprinkler system was simulated to demonstrate the capability of the B-RISK hydraulic model to include the effects of changes in water supply, and to compare the output of the model to sprinkler system statistics. This section describes the setup and results from this simulation.

7.5.1 Compartment geometry

The size of the compartment was chosen to allow 16 sprinklers which ensured the sprinkler system water supply could be overrun without excessive simulation times. Figure 7.12 shows 3-D and sprinkler layout views of the space, which was 16 m square and 2.4 m high with a single open door. A 4 x 4 grid of sprinklers were spaced 4 m apart, with 2 m separation from the walls, which met the spacing (less than

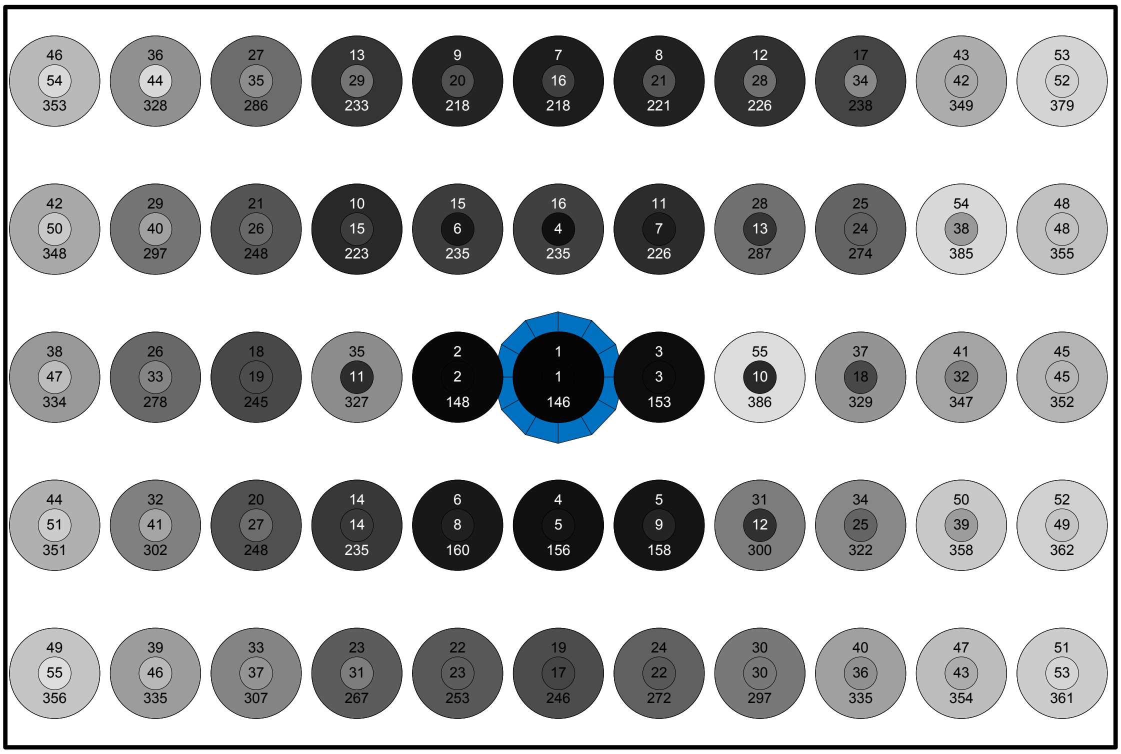

Figure 7.10: Comparison of modelled and experimental sprinkler activation order for Experiment 25. The modelled and experimental orders of activation are shown at the centre and top of each circle, respectively. The bottom number is the experimental activation time.

4.6 m) and coverage (less than 21 m^2 per sprinkler) requirements of NZS4541:2007[5] for an ELH commercial system.

The compartment boundary material was specified to be the B-RISK default concrete material, 100 mm thick. A single 0.8 m wide by 2.0 m tall vent was open for the duration of the simulations, representing a door.

7.5.2 Modelled sprinkler parameters

The sprinklers were modelled as standard response pendant sprinklers with a K factor of 8 $\frac{\text{L/min}}{\sqrt{\text{kPa}}}$ and nominal 68^{o}C activation temperature. Distributions for the sprinkler thermal response parameters are shown in Table 7.2. The sprinkler distance below the ceiling was fixed at 0.1 m, typical for a pendant sprinkler installation and meeting the requirements of NZS4541:2007[5] which required the sprinklers to be

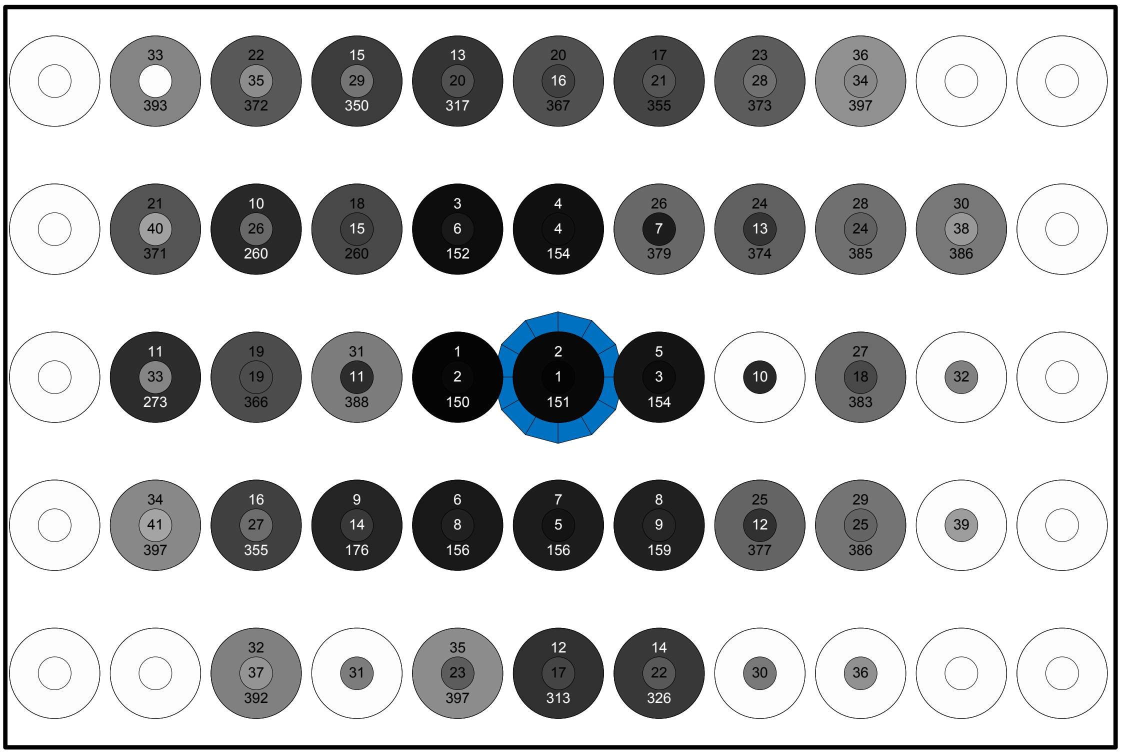

Figure 7.11: Comparison of modelled and experimental sprinkler activation order for Experiment 26. The modelled and experimental orders of activation are shown at the centre and top of each circle, respectively. The bottom number is the experimental activation time.

Parameter	Distribution Type	Distribution Parameters		Source
RTI	Normal	μ=93.4 (m s)$^{1/2}$	σ=4.44 (m s)$^{1/2}$	[21]
C Factor	Normal	μ=0.44 (m/s)$^{1/2}$	σ=0.01 (m/s)$^{1/2}$	[21]
T_{act}	Normal	μ=72^{o}C	σ=0.655^{o}C	[22]

Table 7.2: Distributions for the uncertainty in sprinkler thermal response parameters for the water supply model.

less than 150 mm below the ceiling. B-RISK release version 28 was used for this analysis.

7.5.3 Hydraulic design

The sprinkler water supply was sized to meet the ELH classification in NZS4541:2007. The required number of sprinklers to be supplied for the NZS4541:2007 hazard classes are shown in Table 7.3. 50 mm diameter pipe was specified up to the first

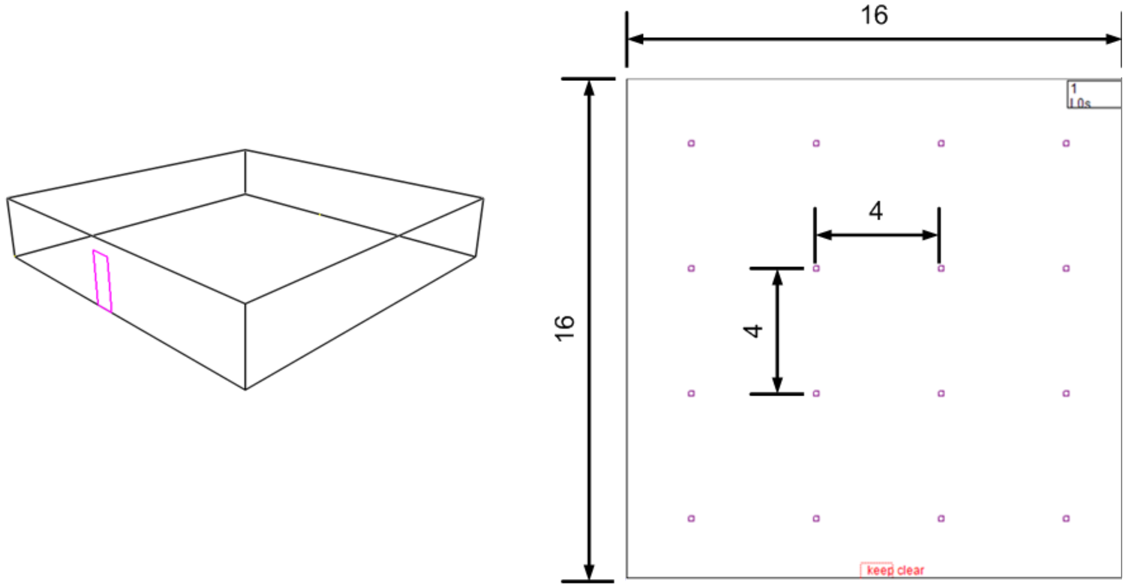

Figure 7.12: Generic compartment used for the water supply model. The left view is the 3-D view and the right is the room population view from B-RISK, showing sprinkler locations as squares.

Occupancy hazard class	**Sprinklers**
ELH (residential)	4
ELH (other)	6
OH1	6
OH2	18
OH3	18
	Sprinklered area (density)
EHH	260 m^2 (7.5-12 mm/min)

Table 7.3: NZS4541:2007[5] minimum number of sprinklers supplied

sprinkler on the branch piping, with the remainder of the piping specified as 38 mm, to meet the hydraulic requirements for an ELH hazard classification system. A three end-side with end supply arrangement was used, and the node numbering scheme for the hydraulic model is shown in Figure 7.13.

7.5.4 Water supply

Typical water supply characteristic quadratic pressure-flow curves were chosen to provide the required pressure and flow. To compensate for water supply fluctu-

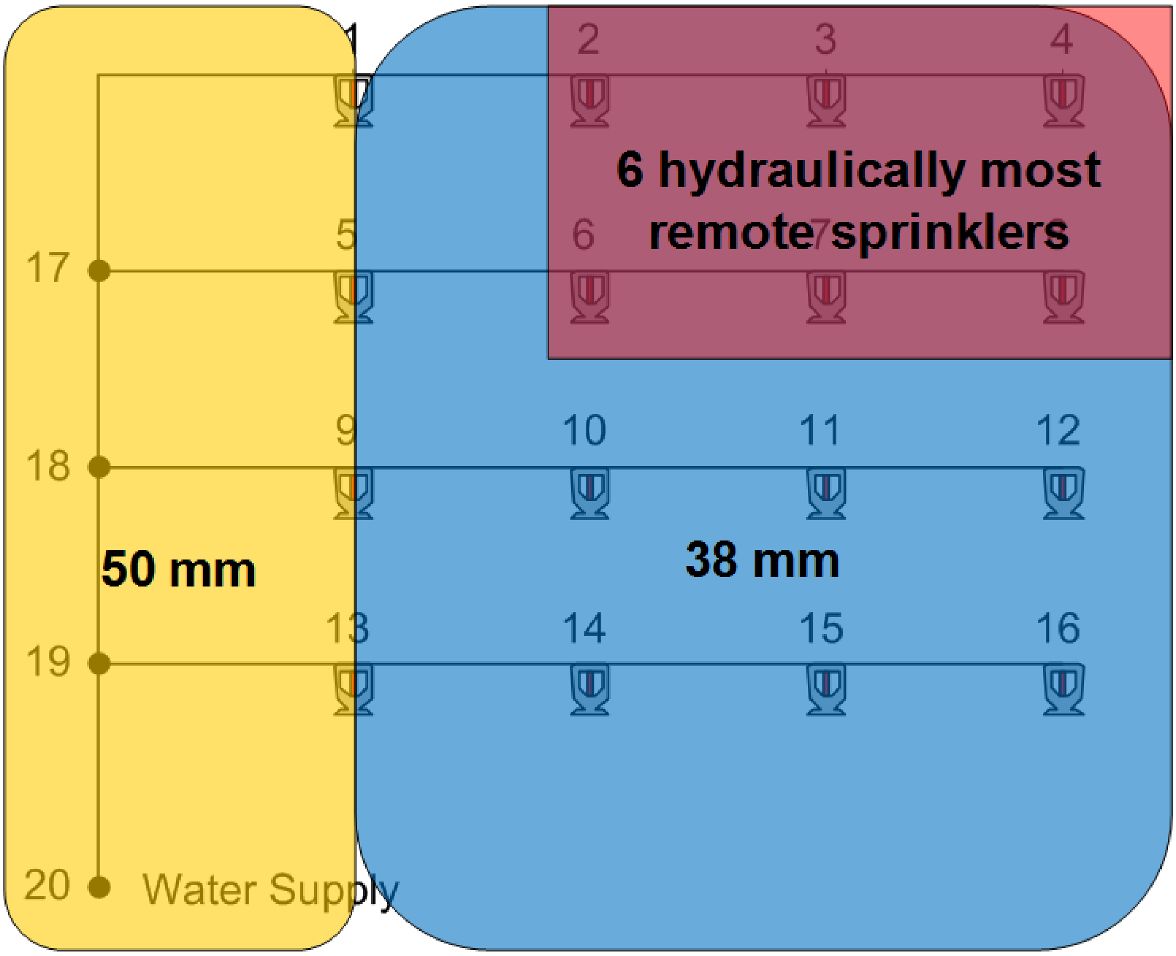

Figure 7.13: ELH hydraulic design. The 6 hydraulically most remote sprinklers are shown.

ations, NZS4541:2007 requires that the measured available water supply must exceed or equal the required minimum water supply depending on how the pressure and flow capabilities of the water supply are measured, and allows two alternative methods for calculating the required minimum water supply. For Method 1, Section C2.6 of NZS4541:2007 states that:

> *The pressure available to meet the design requirements shall be taken as 80% of the pressure indicated by line C of the graph* (the adjusted pressure-flow curve) *at the design flow required.*

Section C2.7 also allows 100% of the pressure indicated by line C to be used if the water supply authority has proposed upgrades to the reticulation system that will improve the pressure and flow characteristics of the system, subject to the approval of the Sprinkler System Certifier (SSC).

Method 2 uses the same methodology as Method 1 to measure flow and pressure, but the pressure-flow curve for the water supply is adjusted further to account for the lowest static pressure as measured over a period of 14 consecutive days (neglecting low pressure spikes due to system hydraulic shocks), or *"if the water supply is liable to seasonal fluctuation, the record shall be taken for at least 21 days during the season when the pressure is at its lowest"* (Section C3.2). It is also left to the contractor to find out if the seasonal low pressure changes from year to year, subject to potential further derating by the SSC. Method 2 allows the design pressure for the sprinkler system to be 90% of the water supply pressure as adjusted for the lowest measured static pressure.

Five water supply scenarios were simulated by adjusting the static head of the supply, shown in Figure 7.14. The water supply supplied the 6 most hydraulically remote sprinklers with the minimum water density of 4.1 mm/min as required by NZS4541:2007 for a commercial occupancy with an ELH hazard classification using a static head of 35 m. For the second water supply scenario, the static head was adjusted up to 44 m to include the requirements of Method 1 of measuring the water supply characteristics in NZS4541:2007. The static head was also adjusted down to 28 m and 22 m to reflect a compromised water supply. Incidentally, the water supply with a static head of 22 m was able to supply the four hydraulically most remote sprinklers with 4.1 mm/min, meeting the minimum requirements for a ELH residential system. A fifth water supply characteristic with a static head of 55 m was used to evaluate the model results for a superior water supply, which also met the minimum requirement of 5 mm/min density for the six hydraulically most remote sprinklers, typically required for OH1 hazard classifications. The sprinkler layout was not adjusted to meet the NZS4541:2007 OH1 requirements (maximum 3.5 m), so this was for a sensitivity check only.

In addition to the five water supply scenarios, the effect of changing the critical sprinkler pressure was also evaluated using both the constant and growing heat release rate options to observe the effects on the number of sprinklers predicted to activate. While NZS4541:2007 specifies a critical minimum sprinkler supply pressure and spray density, there is no justification for the value and it is unclear if sprinkler system efficacy is compromised at these conditions. Two critical sprinkler threshold states were used: NZS4541:2007 pressure and density criteria of 50 kPa and 4.1 mm/min for a 15 mm standard spray sprinkler and an arbitrary reduced critical pressure of 35 kPa and no limit on the minimum spray density. The water

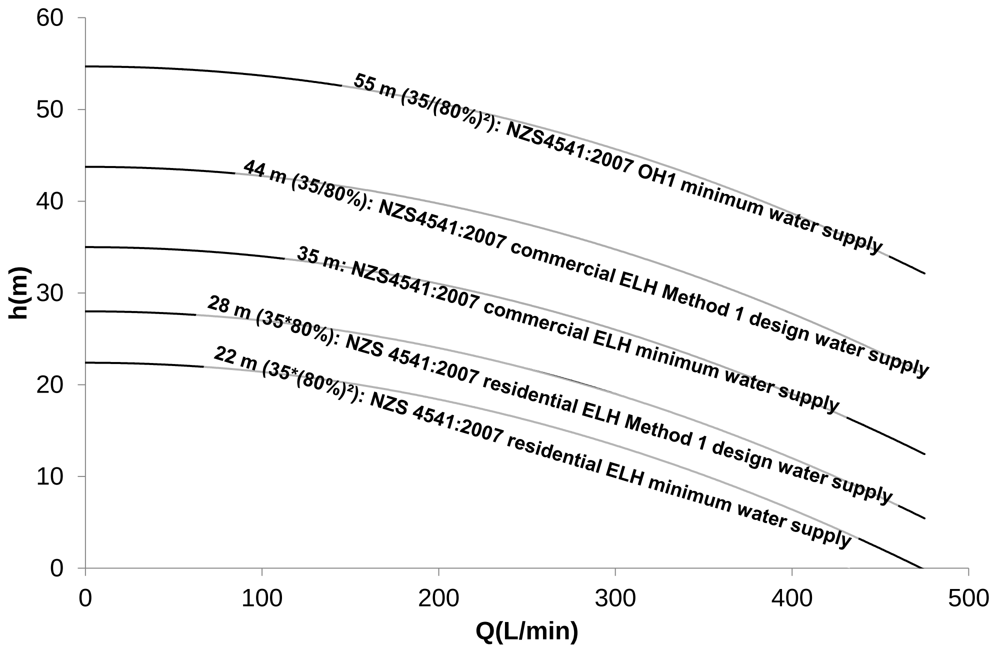

Figure 7.14: Water supply characteristic curves for the water supply model.

supply curve with a static head of 35 m was used. The purpose of this analysis was primarily a sensitivity check on the effect of the critical minimum sprinkler supply pressure and spray density on the number of sprinklers that the B-RISK hydraulic model predicted to activate.

7.5.5 Fire scenario

The αt^2 option of the B-RISK design fire generator was used to create the fire scenarios for the water supply model. For the base scenario, the fire HRR growth distribution from Young[23] previously discussed in Chapter 5 was used. The radiant loss fraction was specified to be constant at 0.35, and the fire height was 0.4 m, meeting the specifications of C/VM2[6]. Total simulated time was limited to ten minutes.

Two additional growth rate distributions developed by Holburn et al[24] from London Fire Brigade data were used to determine the effect of the fire growth rate distribution on the number of sprinklers activated. The distributions used can be

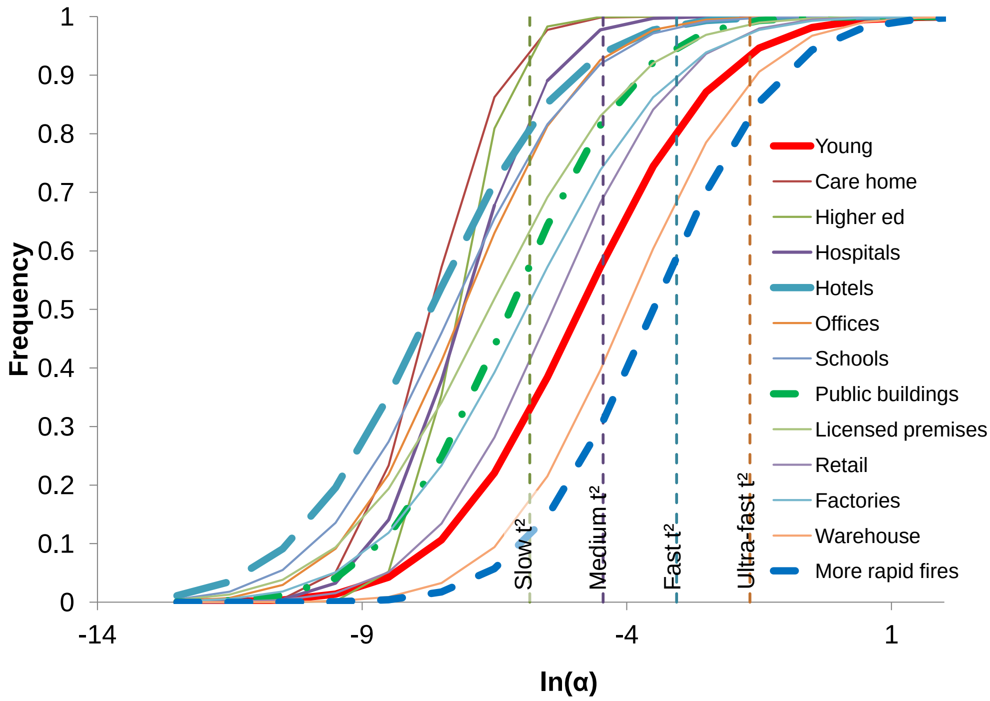

Figure 7.15: Fire growth rate distributions for water supply model from Young[23], Deguchi et al[25], and Holburn et al[24]. The cumulative percentages of fires below the NFPA 72 growth rate classifications are shown for Young's data. The distributions used for the analysis in this chapter are shown as thicker lines.

seen in Figure 7.15, along with additional distributions from Holburn et al and Deguchi et al[25] for comparison. Of the eleven distributions for various occupancies described by Holburn, the hotel and public buildings distributions were selected as representative of the range of occupancy distributions. In addition, an artificial distribution representing a higher probability of rapid fire growth rates which was slightly faster than Holburn's warehouse fire distribution was used as a sensitivity check. The probability percentages for fires to have growth rates between each of the NFPA 72 classifications for the four distributions modelled are shown in Table 7.4.

	Hotels (Holburn et al)	**Public bldgs** (Holburn et al)	**Calorimeter** (Young)	**More rapid fires**
<Slow	81%	58%	33%	11%
Slow - Medium	13%	25%	26%	20%
Medium - Fast	5%	13%	22%	28%
Fast - Ultrafast	1%	4%	13%	24%
>Ultrafast	0%	1%	6%	17%

Table 7.4: Cumulative probability (percentages) for fires to have growth rates in the NFPA 72 classification intervals.

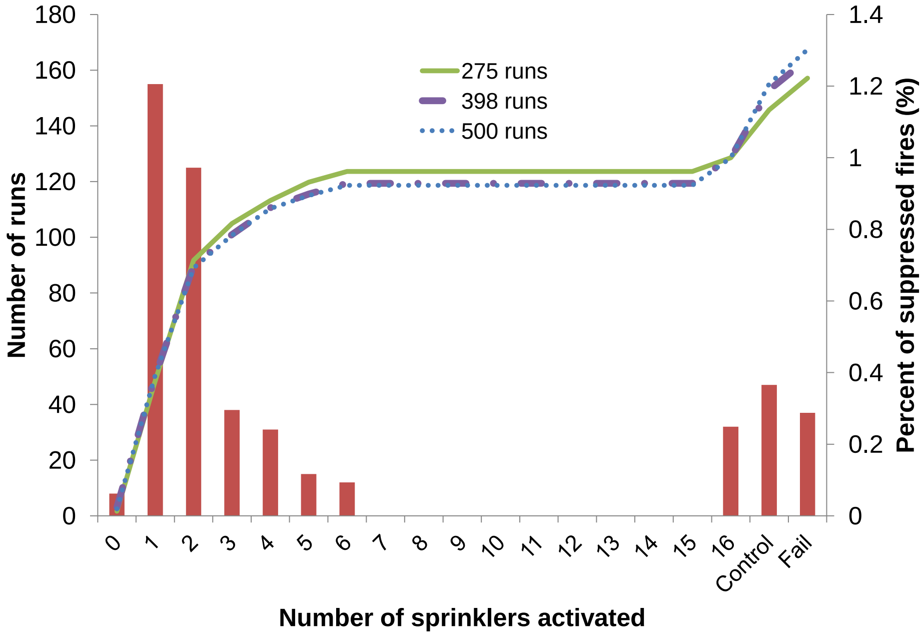

Figure 7.16: Effect of increasing iterations on percentage of cumulative sprinkler activations. The cumulative distribution converged near 500 runs.

7.5.6 Minimum number of iterations for convergence

The base scenario was run with increasing number of iterations to determine the minimum required for convergence of the cumulative probability density output. Convergence was obtained at 500 runs, as shown in Figure 7.16.

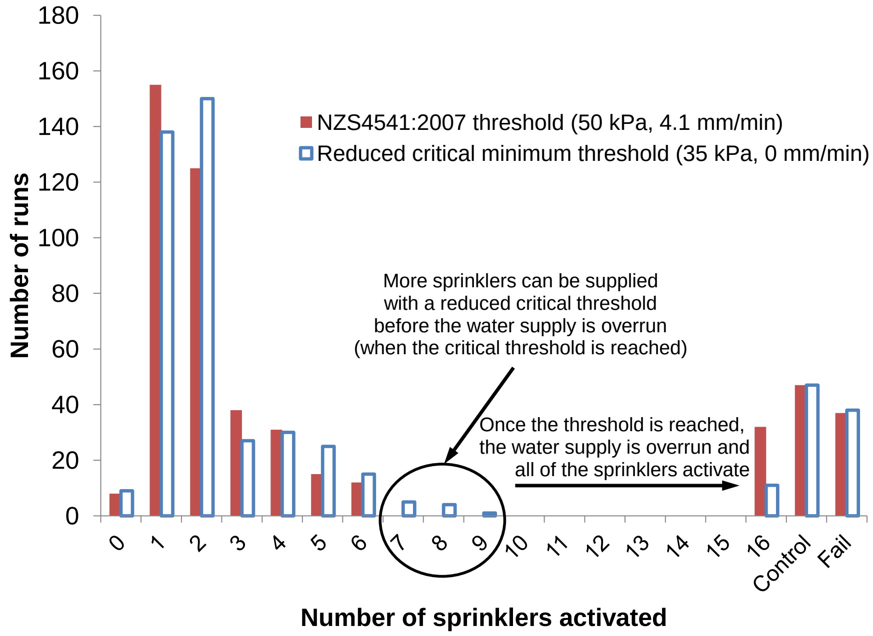

Figure 7.17: Effect of critical water supply threshold on the number of sprinklers activated. Decreasing the critical threshold allowed more sprinklers to activate before the sprinkler system was overrun.

7.5.7 Results

7.5.7.1 Effects of critical sprinkler flow parameters

Once the minimum sprinkler flow decreased below the critical value all sixteen of the sprinklers in the room activated as shown in Figure 7.17. For the commercial ELH minimum supply static pressure of 35 m the critical state was surpassed at six sprinklers as expected with the NZS4541:2007 threshold of 50 kPa and 4.1 mm/min. When the critical sprinkler pressure threshold was decreased to 35 kPa, up to nine sprinklers activated before the threshold was surpassed and the sprinkler system was overrun by the fire.

7.5.7.2 Effects of available water supply

The results of the water supply characteristic scenarios using Young's HRR growth distribution are shown in Figure 7.18, compared to the stem and leaf plot of the reported number of sprinklers activated from Figure 3.3. The number of fires predicted to activate one sprinkler with a commercial minimum ELH water supply (35 m static head supply) is near the bottom of the range reported in fire incident reports, and near the lower quartile for four sprinklers activated and above. The number of sprinklers predicted to activate with the commercial ELH Method 1 design water supply (44 m static head supply) is near the mean of reported sprinklered fires. A compromised water supply with half the static head of the commercial ELH system design requirement (22 m static head supply) is predicted to reduce the number of fires where four sprinklers are sufficient from 91% to 75% (an 18% decrease), for the given scenario geometry and probabilistic design fire input. The decrease in static head to 22 m also caused the sprinkler system to be overrun (when the minimum sprinkler supply flow dropped below the critical value) 25% of the time with more than four sprinklers activated, compared to 2.5% with more than seven sprinklers activated at 44 m static head. The incremental benefit achieved by increasing the static head to 55 m was small with 1.7% of fires overrunning the sprinkler system when more than eight sprinklers were required.

7.5.7.3 Effects of fire growth rate distribution

The results from changing the fire growth rate are shown in Figure 7.19. As expected, more rapid fires resulted in more sprinklers operating. Using the hotel growth rate distribution resulted in 45% of the fires not activating the sprinkler system within the ten minutes of simulated time, which is reflective of the number of smouldering fires that may occur and grow before occupant intervention in sleeping occupancy buildings. As these fires were all idealized t^2 fires, a longer simulated time would have resulted in more fires activating sprinklers. Realistically, the smoke detection system may be set off or an occupant may notice a slow growing fire before the sprinklers activate which would mean that intervention from occupants or the fire service may occur before activation, but these effects were not considered in this analysis.

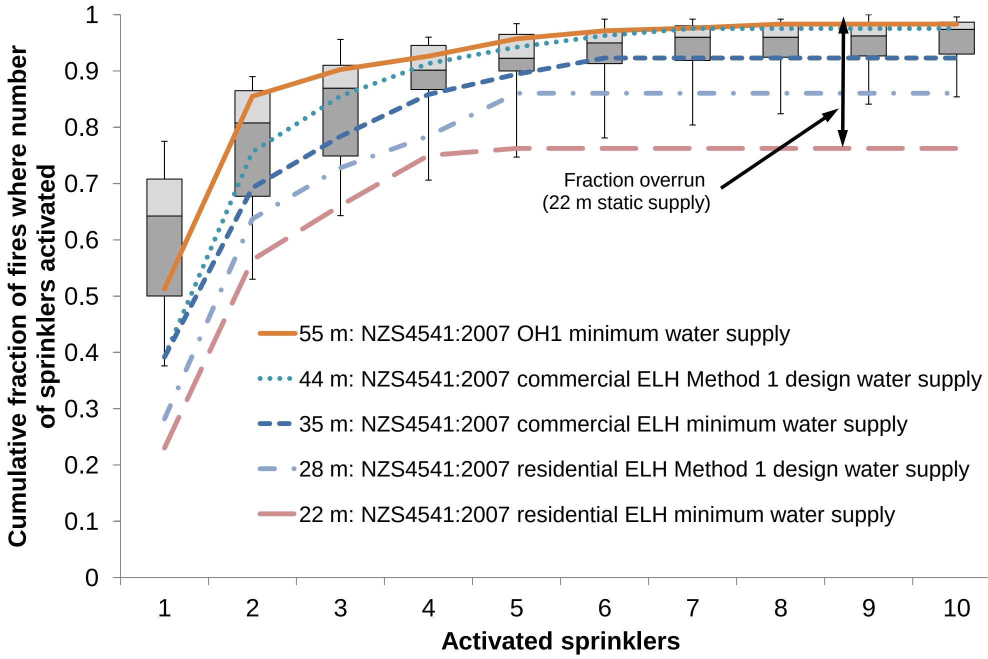

Figure 7.18: Cumulative distribution of active sprinklers for five water supply characteristic curves.

7.6 Conclusions

This chapter describes the methods used to estimate the effects of a sprinkler system on fire development in a new fire design tool being developed in New Zealand. Sprinklers can be modelled as having no effect on the fire, controlling the heat release rate, or suppressing the fire, with associated probabilities. The activation of multiple sprinklers can be estimated; and while such phenomenon as skipping cannot be predicted, an upper bound of activated sprinklers for risk-informed fire safety design is available.

When compared to the Ghent experimental results, using an apparent RTI and activation temperature that gave a predicted activation time for the first sprinkler within 3% resulted in subsequent sprinkler activation predictions closer to the experimental results than using the nominal values for the RTI and activation temperature. More experimental data in a greater range of geometries and with a wider range of fire heat release rate histories would be useful to further validate the model.

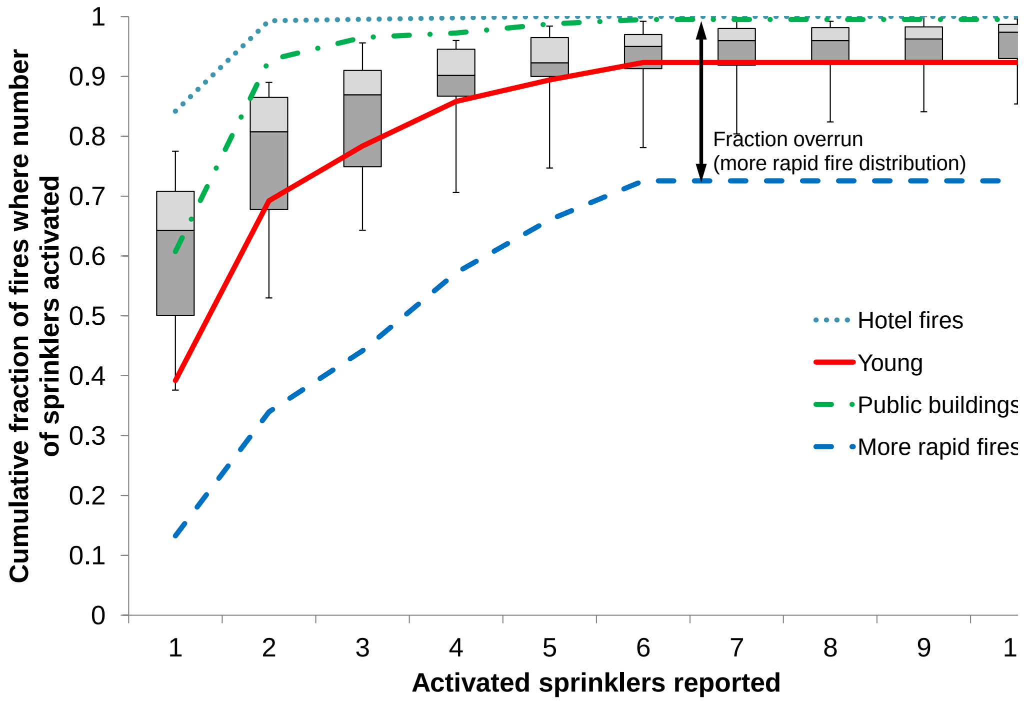

Figure 7.19: Cumulative distribution of active sprinklers for four fire growth rate distributions.

The ability of the model to predict such behaviour could be improved by adding Ruffino's model of evaporative cooling and models for the interaction of the sprinkler spray with the plume and upper layer, but more experimental data is needed for the inputs required for these model refinements.

The ability to estimate the number of sprinklers activated was shown to be useful to estimate the effects of a reduced water supply on fire risk. While the model output using the suppression option appears to match statistical data on the number of activated sprinklers reasonably well, it does not capture the range or complexity of scenarios included in real fire incident studies. Real sprinklered fires include fires in occupancies with high challenge fuel packages, fires that start in concealed spaces or the exterior of the building, and widely varying geometry. In its current state, the hydraulic model might be used as a comparative tool to estimate the change in fire risk from an altered water supply rather than as an absolute tool. Ideally, the data collection improvements suggested in Chapter 4 such as linking water supply characteristic data to fire incident data would be useful in future validation of the capability of the model to include the effects of compromised water supplies on sprinkler effectiveness. The assumption of constant heat release after sprinkler operation seems to be overly conservative as it consistently resulted in the sprinkler system being overrun in both the Ghent experiments and the B-RISK model output.

For the water supply generic commercial scenario modelled, a 50% decrease in static water supply head from the design requirement caused a tenfold increase in fires where the sprinkler system was overrun from 2.5% to 25%, while a 25% increase in static water supply head reduced the number of fires where the sprinkler system was overrun by less than half from 2.5% to 1.7%. This result is specific to the simple room scenario considered and should not be used for actual design scenarios.

The expected sprinkler system behaviour of not operating in smouldering fires was observed in the model when a slow fire growth distribution from hotel data was used. Faster fire growths caused the sprinkler system to be overrun more frequently, so changes in building fuel package statistics should be monitored to evaluate the ability of sprinkler systems to reduce fire risk.

The potential for a sprinkler system to be overrun was shown to be sensitive to the critical minimum sprinkler flow characteristics. More research would be useful to quantify the reduction in sprinkler effectiveness with low pressures.

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CHAPTER 8

PASSIVE SYSTEM RELIABILITY

8.1 Introduction

While effectiveness and reliability are commonly associated with active systems such as sprinkler or smoke management systems, passive compartmentalisation components are also subject to failure due to a number of factors. A few of the most common are propped-open doors (Figure 8.1), improperly fire stopped holes cut through walls, ceilings, or floors for building services, and open windows. Compartmentalisation is critical for fire safety because it determines how much oxygen is available for the fire through ventilation and the available paths for fire products to spread out of the compartment of fire origin. An open door, window, or other penetration in a compartment boundary can adversely affect the operation of a smoke control system, as will be discussed in Chapter 10.[1]

Much work has been done on *"structural"* fire engineering that focusses on how long a particular passive element such as a wall, ceiling, floor, door, or window will stand up to a severe thermal insult typically associated with post-flashover or free burning fires[2]. As this research is focussed on the pre-flashover stages of the fire, the primary concern is the status and integrity of the passive compartmentalisation prior to the fire, and specifically on doors. In addition, the uncertainty in the vent flow calculated by B-RISK is estimated from verification data.

8.1.1 Types of doors

Doors can be categorised by motion:

- swinging (hinged)
- sliding or rolling

method of operation:

- fully manual (both open and closed)
- automatic door closer (spring operated, motorised, gravity system)
- automatic hold open device (magnetic)

and ability to prevent fire and smoke spread:

- no rating
- smoke stop
- fire rated

Even doors that are not “fire rated” can make a significant difference in the spread of smoke and flame through a building, as observed in a residential fire in Papakura, New Zealand[3], where a house was gutted by fire except for the one occupied bedroom. As the fire breached the top of the door, a smoke alarm in the room alerted the occupant who had enough time to escape safely through the window. Palmer[4] compared the fire risk between sleeping in a typical house bedroom with the bedroom door open and closed and found that fire risk was reduced with a closed bedroom door. In most cases for the purpose of modelling fire, doors that are not expected to perform as smoke stop or fire doors will be considered to be open at all times, as specified in C/VM2[5].

Based on observations in New Zealand buildings during this research, the most common type of smoke stop or fire door in residential and commercial occupancies is the swinging door, in either single leaf or double leaf configurations, with self closers, with or without automatic hold open devices.

Figure 8.1: A typical fire door failure.

8.2 Existing data sources

Bukowski et al[6] noted that there was very little data regarding performance of individual passive elements, although there are two sets of expert surveys cited that indicate probabilities that an opening will be fixed open; the Warrington Delphi UK study estimated the probability that an opening will be fixed open is 29%, and the Australian Fire Engineering Guidelines estimated that the reliability of a passive element (such as a wall) should be reduced from 95% to 90% if an opening with an automatic closer is present. Quoting other unknown data sources, PD7974-7:2003[7] indicates that up to 23% of fire doors are held open by some means that will not release in case of a fire, and of the hinged fire doors that are not blocked open, 20% may fail to close correctly.

Yashiro et al[8] reported estimates of the reliability of fire doors with automatic closers and inter-lock devices, as well as fire shutters, from Tokyo Fire Department data. Fire doors with automatic closers were estimated to be 97% reliable, 91% reliable when inter-lock devices were used, and fire shutters were also estimated to be 91% reliable.

There is little data on the number of inadequately sealed penetrations in compartment walls, ceilings, and floors other than doors and windows, such as those for building services. A survey of 11 buildings conducted by the Fire Protection Association of New Zealand (FPANZ) found a variety of inadequately fire-stopped penetrations, including large open cable trays, oversize holes for pipes and improperly stopped fire shafts[9].

Beyler and Iwankiw[10] discussed compartmentalisation for record storage occupancies and discussed passive reliability, including improperly fire stopped penetrations and fire door failures. No specific data on penetration or door reliability was presented. Fernandez[11] noted that nuclear facility inspectors found fire doors propped open, however no quantitative data was reported. Testing conducted by Factory Mutual in the early 1990s indicated that the failure rate of fire doors including horizontal sliding doors on inclined tracks, horizontal sliding doors with counterweight closures, horizontal sliding doors with spring closures, vertical sliding doors, and swinging doors in Maximum Foreseeable Loss walls was 15%[12].

Lustig[13] examined the status of doors and windows in 250 fires in dwellings in the UK over a period of five years in the 1950s. It was indicated that while there was not enough information gathered to statistically determine the effects of open windows and doors on fire development, but specific case histories indicated that closed doors and windows had a significant effect on fire development. In three cases, a fire ignited but either burned out or was undetected in a closed room and did not damage other areas of the residence. In two cases, it was noted that open doors allowed fire to spread rapidly. In one case, a fire on the first floor of a dwelling spread upstairs through open doors to two bedrooms, where four people died. There were two people rescued from a room on the first floor where the door was closed. Lustig also noted two examples where a closed door prevented early discovery of the fire.

Ramachandran[14] discussed the status of fire doors in 28 buildings reported to be equipped with fire doors where large fires occurred during 1965 and 1966 in the UK. While door position data at the time of fire was only available for 19 of the fires, it was found that fire doors were open in 5 fires, or 26% of the fires with known door positions.

A 1970 study by Langdon Thomas and Ramachandran[15] looked at data on

Occupancy	Number of doors observed	% propped open
Dwellings	9,887	17
Office buildings	7,055	18
Institutional buildings	15,558	39
Schools	14,102	23
Shops and department stores	3,371	26
Assembly buildings	18,435	5
Factory buildings	22,491	15
Storage buildings	1,010	37
Total	**91,909**	**19**

Table 8.1: Frequency of doors observed to be propped open from 1970 UK study[15].

fire doors propped open provided from fire brigade inspection visits in the UK. A summary of the results of their study is shown in Table 8.1.

8.2.1 Construction leakage

Walls and floors in most occupancies are not sealed air-tight. Klote and Milke[16] provide typical leakage areas for a variety of commercial building elements including doors, walls, and floors. Leakage area ratio values for walls and floors are given for a range of building construction from loose to tight, which may be used to estimate a distribution for the leakage area.

8.2.2 Door leakage

Doors that are closed are usually not tightly sealed and will allow some passage of fire gases and fresh air in and out of a fire compartment. Edwards and Wade indicated that leakage rates through doors depend on temperature, time and components of the door assembly[17]. AS/NZS 1530.7:1998, does not specify a maximum leakage rate for smoke control door assemblies, but provides a guideline of 20 to 25 m^3/hr maximum leakage rate per door leaf where life safety is the main fire risk concern, based on information from other countries[18]. Klote and Milke[16] give flow areas for doors based on gaps and construction. [19]

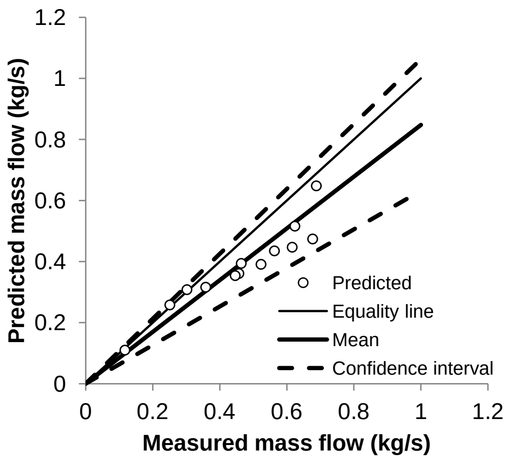

Figure 8.2: Estimate of vent flow uncertainty from reported verification data[20]. The mean and two standard deviation confidence interval of the uncertainty are shown.

8.3 Vent mass flow model uncertainty

As mentioned in Chapter 1, B-RISK includes routines for estimating the flow of fire products and fresh air through vents. The epistemic uncertainty in the flow through a vertical vent was estimated from the Steckler verification data[20] previously described in Section 5.4.4. In these tests, vent flow through a variable size vertical vent was measured with a steady state fire of varying size from 32 kW to 158 kW in a 2.8 m x 2.8 m x 2.13 m tall compartment. BRANZFire simulations varied from the experimentally measured vent flows with a mean of -15% and a standard deviation of 11%. The estimated model uncertainty in predicting the vent mass flow using the BRANZFire deterministic two-zone fire physics engine is shown in Figure 8.2.

8.4 Conclusions

This chapter has summarised available data on the probability that vents, specifically doors, are open at the start of a fire. This data can be used as a basis for estimating the vent openings in B-RISK models. A brief discussion of the uncertainty in the vent mass flow model for B-RISK based on comparison to one set of experimental data is also included. Chapter 9 discusses a new method for collecting fire door reliability data.

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CHAPTER 9

DOOR RELIABILITY DATA COLLECTION

9.1 Introduction

As existing data on fire door reliability was sparse, a new method of collecting data on fire door operation was developed, consisting of a low cost, unobtrusive logging device capable of collecting several months of door position data. A major disadvantage of the existing data on door reliability is that it is typically compiled from inspection data. This approach provides a "snapshot" of the position of the door in time but does not provide information on how the position of the door has changed over time. For example, a door might be propped open at certain times of the day when it is heavily used. The propensity of occupants to prop open a door might be seasonally dependent or day-of-week dependent, if the usage of the building varies over these time periods.

The devices were tested for two conditions: to identify the length of time that a door might be open during an evacuation, and the probability that a door might be open at the time a fire occurs. Data for the first condition was collected during trial evacuations from two university buildings and data for the second condition was collected over a longer time period of six months in 13 sleeping occupancy buildings.

Data from the devices may be useful for a variety of stakeholders. Persons developing building regulations or fire safety practitioners using performance-based design might use the reliability data to determine the contribution of fire and smoke doors for reducing the spread of fire and smoke through buildings. Fire door and door closer manufacturers might be interested in collecting data on their devices to determine usage patterns. Building managers may be interested in knowing the usage patterns of doors in their buildings. Fire safety researchers who examine human factors in fire may also be interested in data on the use of doors during evacuation or fire fighting.

9.2 Door position data logger design

The hardware and low-level software design of the door reliability data logging device went through two major iterations and a third minor update. The first iteration was developed with the assistance of Mr. Tim Crow for his undergraduate electrical engineering design project, and subsequent versions were developed with the assistance of Mr. Forrest McKarcher for his electrical engineering professional practical work requirement. The following sections describe the development of the device. The schematic for the final version of the devices can be seen in Figure 9.1, and the layout of the major components in the devices can be seen in Figure 9.2.

9.2.1 Microcontroller

The Texas Instruments MSP430 family of microcontrollers was selected based on power consumption, price, and ease of programming. The first version of the device used the Texas Instruments MSP430F2132, which did not have onboard wireless communications capabilities. Thus, a USB connection was used to download data directly from the device mounted on the door. This had the disadvantage that a cable would have to be connected directly to the device on the door, both for initial setup and calibration and for downloading data at the completion of the test period, as well as any interim checks to identify if the battery and memory still had sufficient capacity to continue logging data. Wireless solutions were researched to solve this problem.

The CC430 was identified as a suitable System on a Chip (SoC) with wireless communication capabilities while still meeting the cost and power consumption requirements[1]. Subsequent versions used the Texas Instruments CC430F5137 which has an onboard radio for wireless interfacing. The CC430 has a low power mode

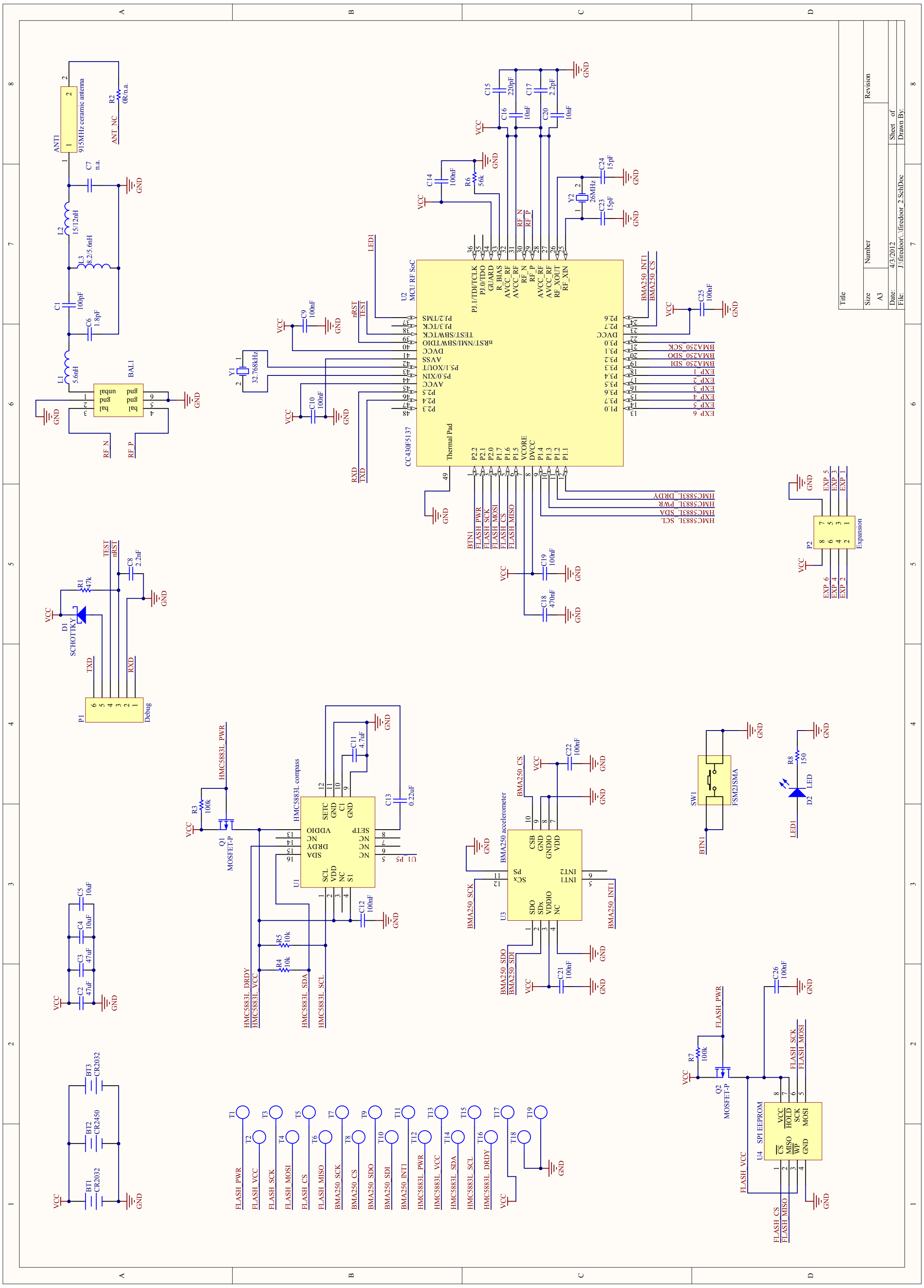


Figure 9.1: The schematic for the final version of the door position logging device. Note: The 100kΩ resistors were replaced with 10MΩ resistors to reduce current consumption.

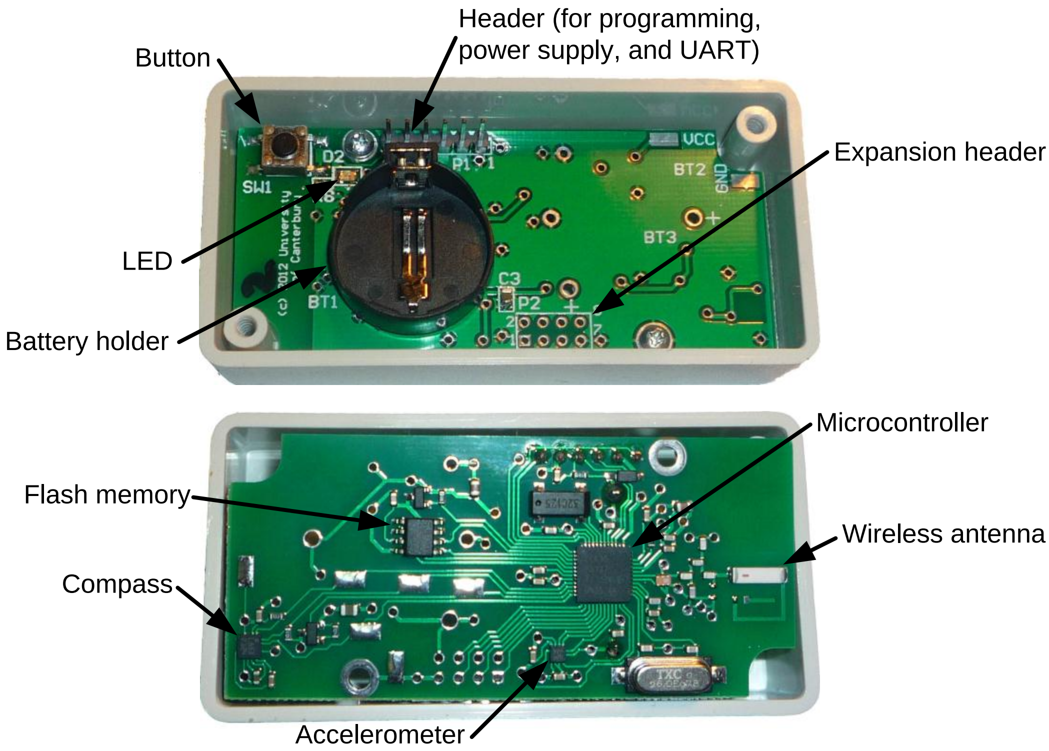


Figure 9.2: Major components in the final design of the door data logging devices.

that keeps the real time clock active, retains the contents of RAM, and allows interrupts to be monitored, with a power consumption of 2 μA. The allowable supply voltage ranges from 1.8 V to 3.6 V.

9.2.2 Interface

The logging device mounted directly on the door was set up to communicate wirelessly with an RF bridge device at 915 MHz at 250 kbps (kbaud). This RF bridge, which also utilises the CC430F5137 microcontroller, then communicates to a PC via the CC430 Universal Asychronous Receiver/Transmitter (UART) peripheral and a FTDI UART to USB converter, as shown in Figure 9.3. The RF bridge to PC connection operates at 460.8 kbps (kbaud). Communication is initiated by pressing a button on the data logging device which signals the microcontroller to switch from "normal" mode (or the data logging configuration) to "debug" mode (the communication configuration. The data logging device is returned to normal mode by either

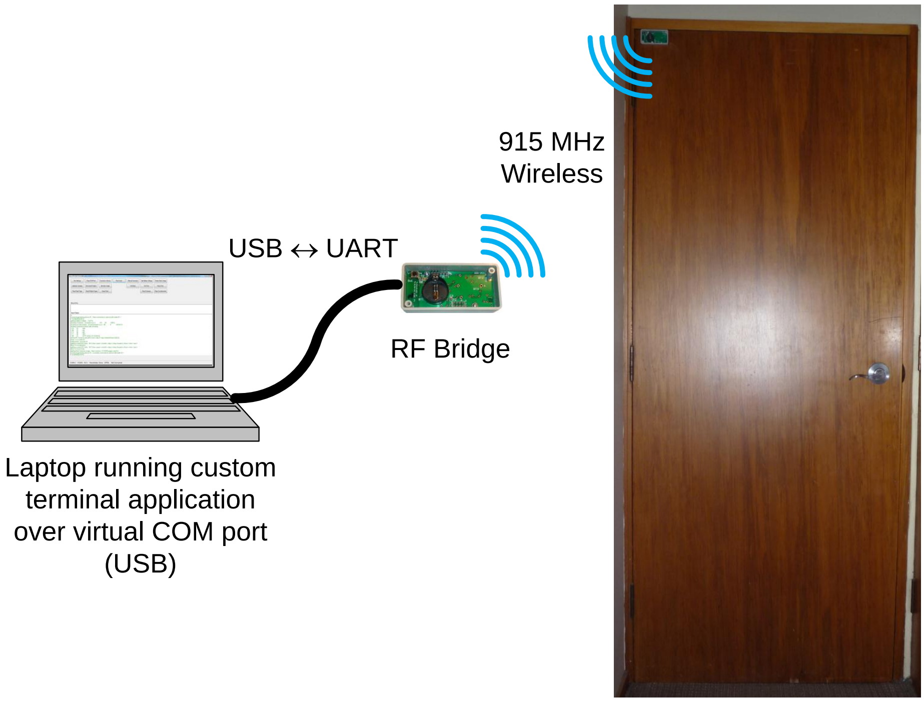


Figure 9.3: The interface between the fire door position data logging devices and a PC. Wireless 915 MHz communication is used for communication between the door mounted devices and an RF bridge device, and a UART to USB connection is then used to interface with a PC.

a timeout or a command from the PC to disconnect the device. Figure 9.4 shows how the data logging device software was configured to switch between the normal and debug mode.

A custom terminal program was written using VB.NET to send and receive information from the PC to the data logging devices. A screenshot of the program can be seen in Figure 9.5. The use of a custom terminal program reduced the amount of time required to setup and download data from the devices. A particular advantage was the ability to syncronise the real time clock on the devices with a laptop clock using a single click rather than manually entering the time.

9.2.3 Sensors

Several different types of sensors were considered. The first option was a rotary potentiometer, measuring the door angular rotation using the potentiometer's variable

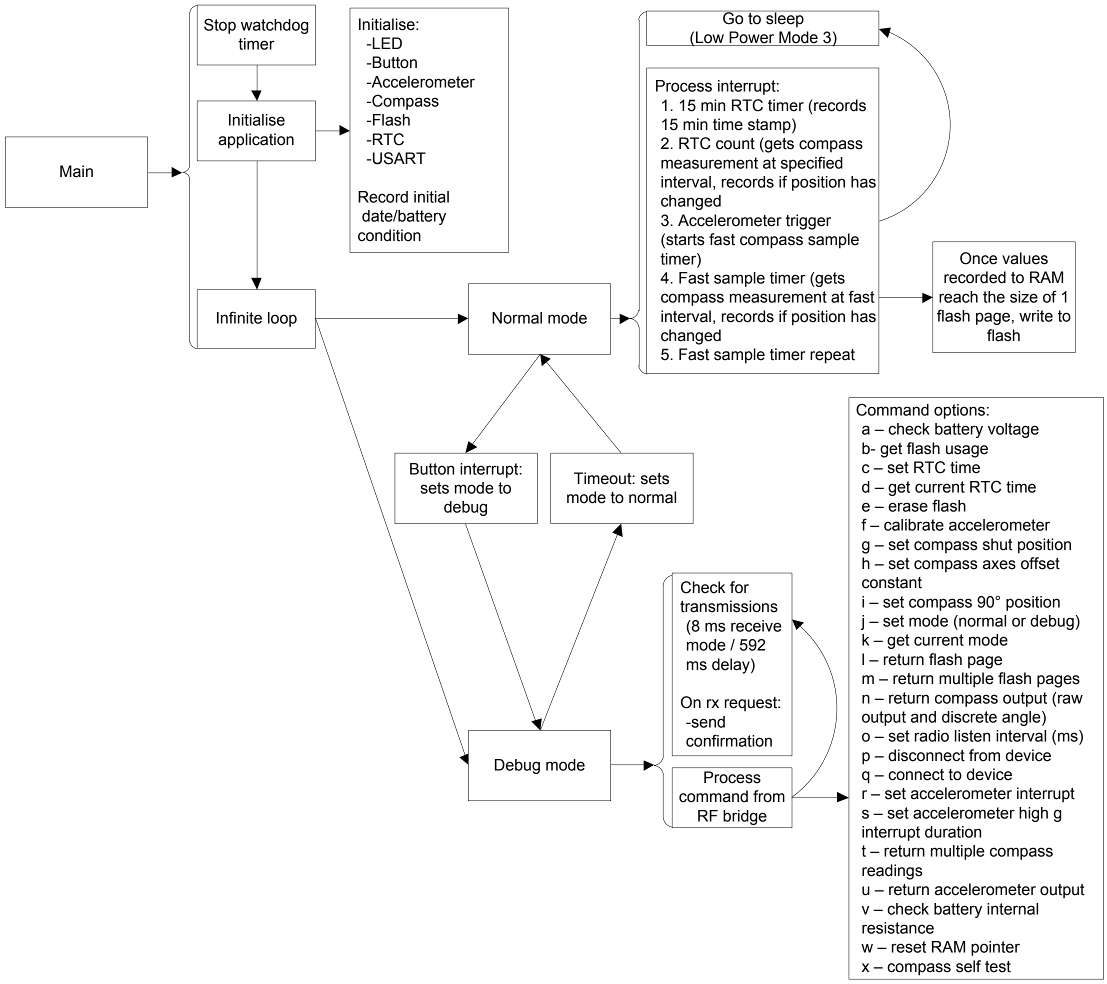


Figure 9.4: Software flow for the fire door data logging devices. After the watchdog timer is switched off and the pins, peripherals, sensors, and memory are initialised, the device enters normal mode. Debug mode is entered by a button press, and the device returns to normal mode after a timeout or command from the user.

resistance in a voltage divider. This would have required a fixture to be designed for the potentiometer at the pivot point of the door, perhaps mounted on one of the door hinges. A second option was a capacitive distance measuring sensor, which would have required two plates mounted on the door and frame to measure the change in capacitance as the plates moved away from each other. Other proximity sensors such as optical sensors or ultrasonic sensors could be used but the signal could get blocked by interfering objects. Gyrometers, which measure rate of rotation, could have been used by integrating the rate of rotation over time. This option was discarded due to the potential for cumulative integration errors over time. Mag-

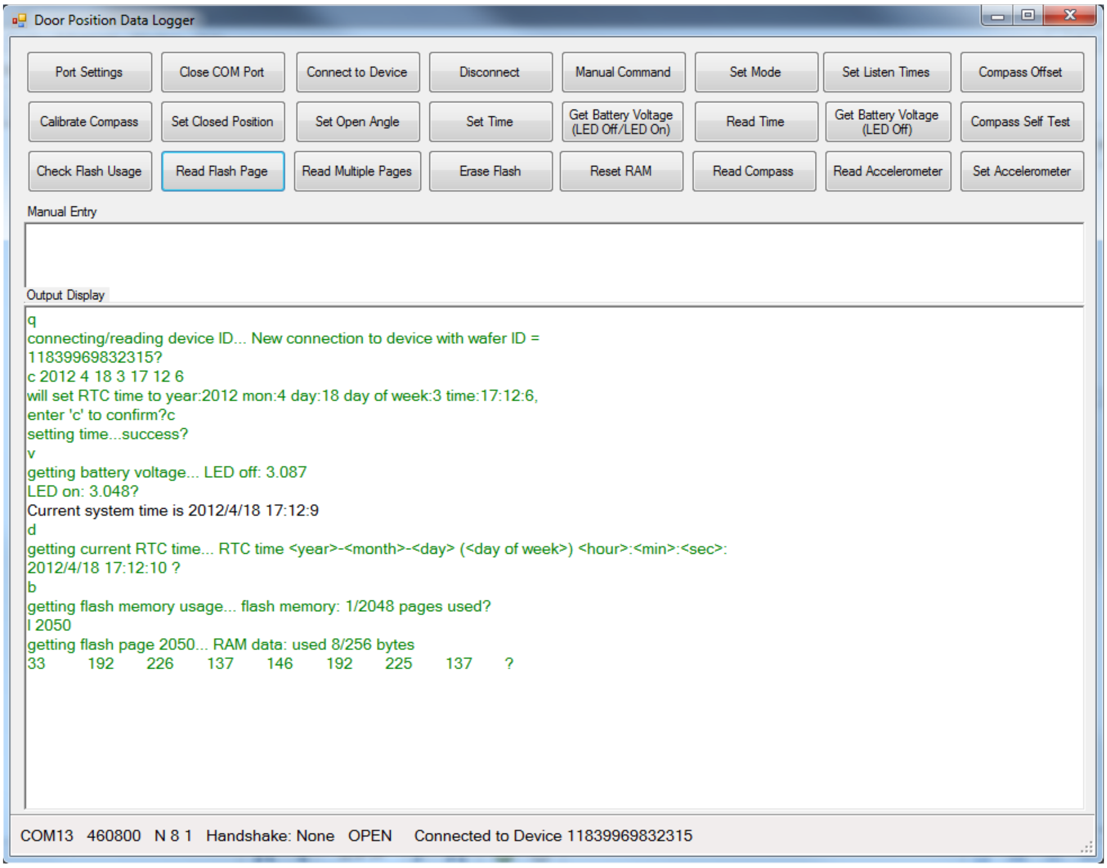


Figure 9.5: Custom terminal program written to send commands to and receive data from the door position logging devices.

netometers used as a compass to measure the door's angular position relative to the geomagnetic field were the option selected. The advantage of the magnetometer approach was that the sensor could be mounted anywhere on the door, and did not require an additional fixture on the door frame or adjacent wall. Also the orientation measured by the magnetometer or compass was independent of time, although a potential disadvantage was erroneous readings due to nearby objects influencing the magnetic field.

Investigation into the cost of the sensors found that the price of surface mount electronic magnetometers was reasonable, likely due to their widespread use in smart phones, tablets, and navigational devices. The magnetometer or compass selected was the Honeywell HMC5883L, a 3 axis magnetometer with I2C interface capabilities, low power consumption, and low cost[2]. The HMC5883L has a resolution of one to two degrees of rotation, depending on the strength and orientation of the geomagnetic field at the location where measurement is taking place. It takes 200 μs to turn on and be ready for I2C commands, and a further 6 ms to be able to send data. A data ready interrupt pin can be monitored to ensure that data is sent as soon as the device is ready. The device draws approximately 100 μA in measurement mode, and operates with a supply voltage down to a minimum of 2.16 V.

To optimize memory and power requirements, the BMA250 3 axis accelerometer from Bosch was selected, which could be used in a motion sensing configuration to allow the rest of the circuitry to remain at idle while the door was stationary[3]. The resolution of the BMA250 on the minimium scale setting of 2g (2 times the acceleration due to gravity) is 256 bits/g, or 0.038 m/s^2. The accelerometer can operate on a wide voltage range from 1.62 V to 3.6 V, and uses 7 μA in low-power mode with a sleep duration of 25 ms (time between samples) using unfiltered data. It can be operated in a dedicated mode that does not require any microcontroller interaction while still maintaining the interrupt engine.

The accelerometer has a variety of interrupt-trigger modes; the slope detect and high g-force two were evaluated for indicating door motion. The threshold, duration, and axes utilized for both modes could be be set by the user. The slope detection method triggered the interrupt when the change in acceleration exceeded a user-defined threshold for a user-defined duration. The high g-force method triggered the interrupt when the magnitude of the acceleration exceeded a user-defined threshold for a user-defined duration. Both methods were used on the z axis of the accelerometer.

Unfortunately, it was found that the accelerometer interrupt provided excessive spurious signals unless the low pass filter was set to 8 Hz. To acquire enough signals to filter the data to 8 Hz required the accelerometer to be on for 64 ms for each slope calculation, which caused the current consumption to increase above 100 μA, which meant that the accelerometer was using more power than the compass for measurement. However, the accelerometer is still useful when using the devices for evacuation position logging where increased time resolution is desired.

The accelerometer and magnetometer were oriented to produce x, y, and z output as shown in Figure 9.6. The ground plane was removed from the back side of the board in the magnetometer location as recommended in the compass datasheet. The magnetometer was also located on a corner of the board as far away from other

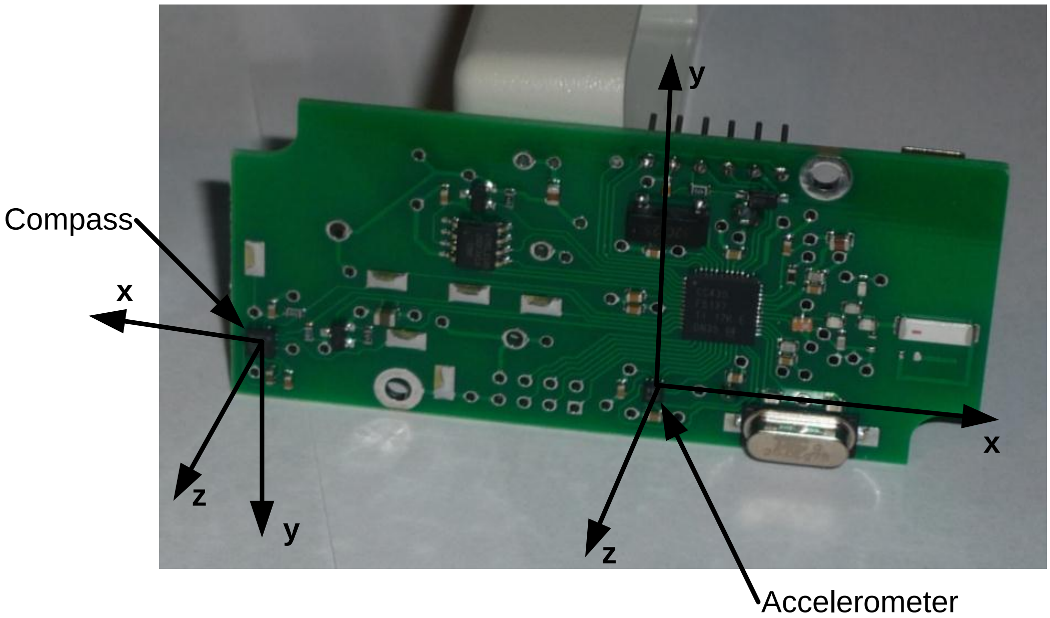


Figure 9.6: Orientation of the compass and accelerometer axes.

components (particularly the battery) as possible to reduce circuit electromagnetic and component ferromagnetic effects on the measured magnetic field.

9.2.4 Memory

Electrically Erasable Programmable Read Only Memory (EEPROM) and flash memory were evaluated for use in the data logging device. While EEPROM memory used less current for reading and writing, the flash memory was cheaper and available in larger capacities. A 4 Mbit flash memory chip (Atmel AT25DF041A) was chosen based on the expected memory requirements for the project[4]. Of the components selected, the flash memory has the greatest supply voltage limitation, with a range of 2.3 V to 3.6 V. The flash uses a maximum of 10 mA to read data and 18 mA to write data.

9.2.5 Power source

To keep the size, weight, and cost of the door logging device down, a CR2032 primary lithium ion "coin" battery (typically used for watches and other small electronic devices) was selected. The CR2032 met the requirement of a nominal 3 V supply required by the electronic components, and could supply approximately 180mAh of current before dropping below the minimum voltage of 2.3 V required by the flash memory. The device board has additional through-hole connections to add another CR2032 or CR2450 (620 mAh capacity) battery holder in parallel. The enclosure is also big enough to fit one of these additional batteries. However, it should be noted that the presence of the additional battery will offset the compass measurements because of their proximity to the compass.

9.2.6 Enclosure

A plastic ABS box produced by Hammond Manufacturing was selected for the device enclosure. The dimensions of the box, 40 mm x 80 mm x 20 mm, were adequate to house the device while being small enough to be unobtrusive and lightweight enough to be easily supported by the adhesive poster strips discussed below. Embossments for printed circuit board mounting screws were designed into the box. The box was also inexpensive since it is mass produced.

9.2.7 Fastening system

A fastening system that would secure the device to doors adequately but not permanently damage or alter the doors was required. The fastener had to support the weight of the device which was 40 g, including battery. 3M CommandBrand poster strips were tested and found satisfactory.

9.3 Data logger cost breakdown

Table 9.1 includes the purchase cost of the components at the time of purchase in early 2012 for quantities of 1 and 100. Significant cost savings per unit were realised

Description	NZD (per device)	NZD (per device, 100 qty)
Passive Components	$ 4.59	$ 2.72
CR2032 coin cell holder	$ 0.85	$ 0.74
P-channel mosfet	$ 1.20	$ 0.88
26MHz crystal	$ 0.91	$ 0.58
32768Hz crystal	$ 0.95	$ 0.62
5.6nH +/- 0.3nH inductor 0603	$ 0.18	$ 0.16
12nH inductor 0603	$ 0.09	$ 0.08
896MHz balun	$ 1.48	$ 0.99
915MHz chip antenna	$ 1.63	$ 1.08
Schottky diode SOD-123	$ 0.97	$ 0.34
Red LED 0805	$ 0.27	$ 0.15
Pushbutton	$ 0.55	$ 0.31
Compass	$ 5.05	$ 2.72
Microcontroller + radio	$ 8.99	$ 7.21
Accelerometer	$ 4.72	$ 4.42
4mbit 2.3v SPI flash	$ 1.57	$ 1.19
Casing, grey, 80x40x20mm	$ 3.46	$ 2.33
Casing screws	$ 0.20	$ 0.11
CR2032 cell	$ 0.37	$ 0.32
6-pin single row header	$ 0.72	$ 0.24
Total	**$ 38.75**	**$ 27.19**

Table 9.1: Cost breakdown of components used for the door position logging devices. Components purchased from Digikey.

by building over 100 units. Further discounts were available for larger quantities but the scope and budget of the project would not allow expanded production. The boards were custom manufactured in China at a cost of 174USD for 13 panels of 8 boards (a total of 104 devices)[5]. The boards are shown in Figure 9.7. A solder stencil was also sourced from China for 165USD, which was used to apply solder paste to the boards as shown in Figure 9.8. Assembly was completed by the author and Forrest McKarcher over a period of approximately one week. A pick-n-place machine was used to place surface mount components which were then soldered with a reflow oven. Through-hole components were hand soldered.

Other assorted expenditures included approximately 100NZD for solder paste, 20NZD for a FTDI USB to UART converter, and labels. An electrical engineering undergraduate student (Forrest McKarcher) was employed from November 2011 to February 2012 to design the hardware layout and the code for the radio and interface from the microcontroller to the sensors, memory, and PC which cost approximately

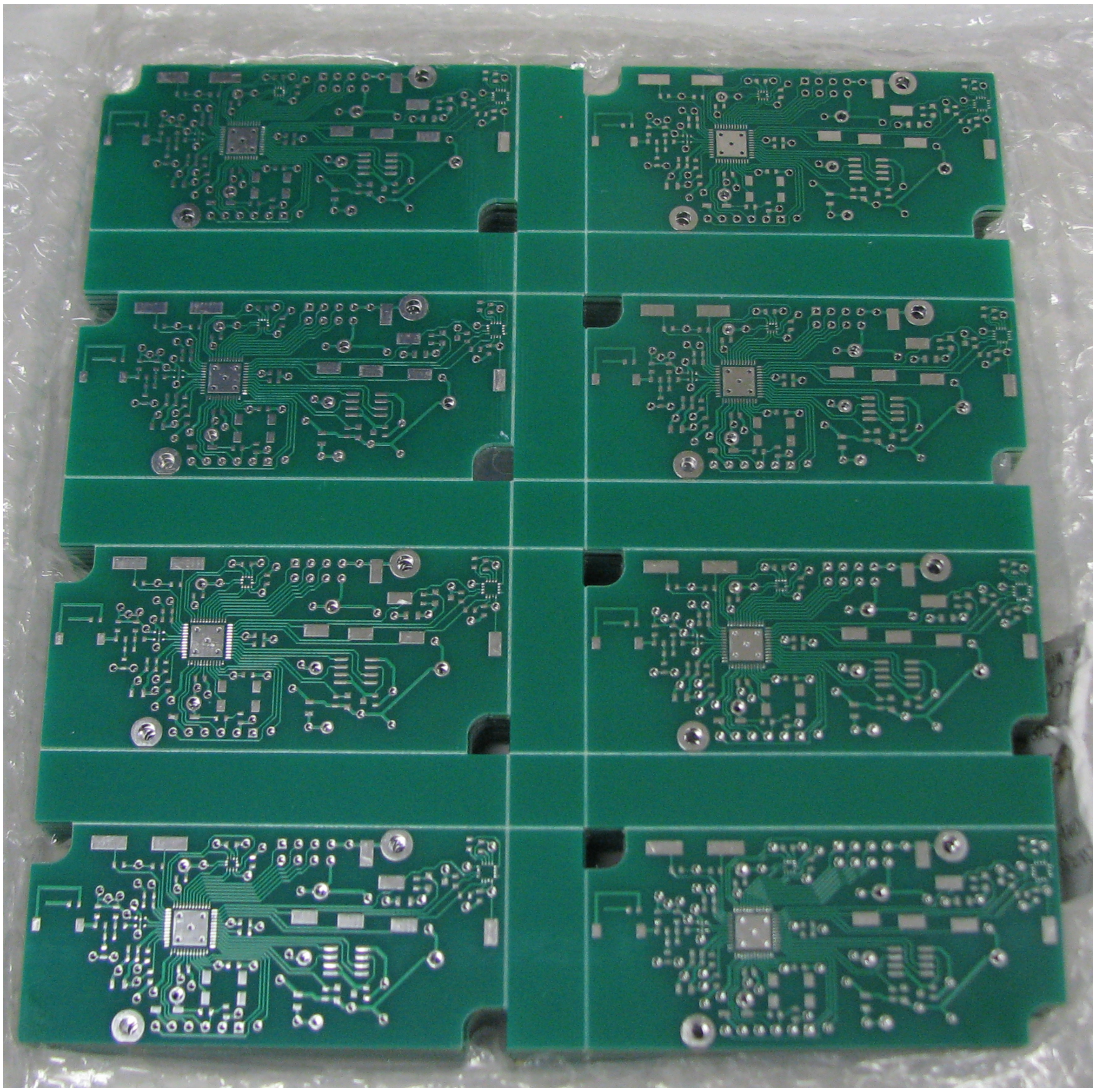


Figure 9.7: Panel of 8 boards as received from the manufacturer in China.

8,000NZD.

9.4 Current testing

Tests were conducted to estimate the amount of power the devices would use during testing. A resistor was placed in series with a data logging device. By measuring the voltage across the resistor, the current through the resistor (and therefore the device) could be calculated by using Ohm's Law:

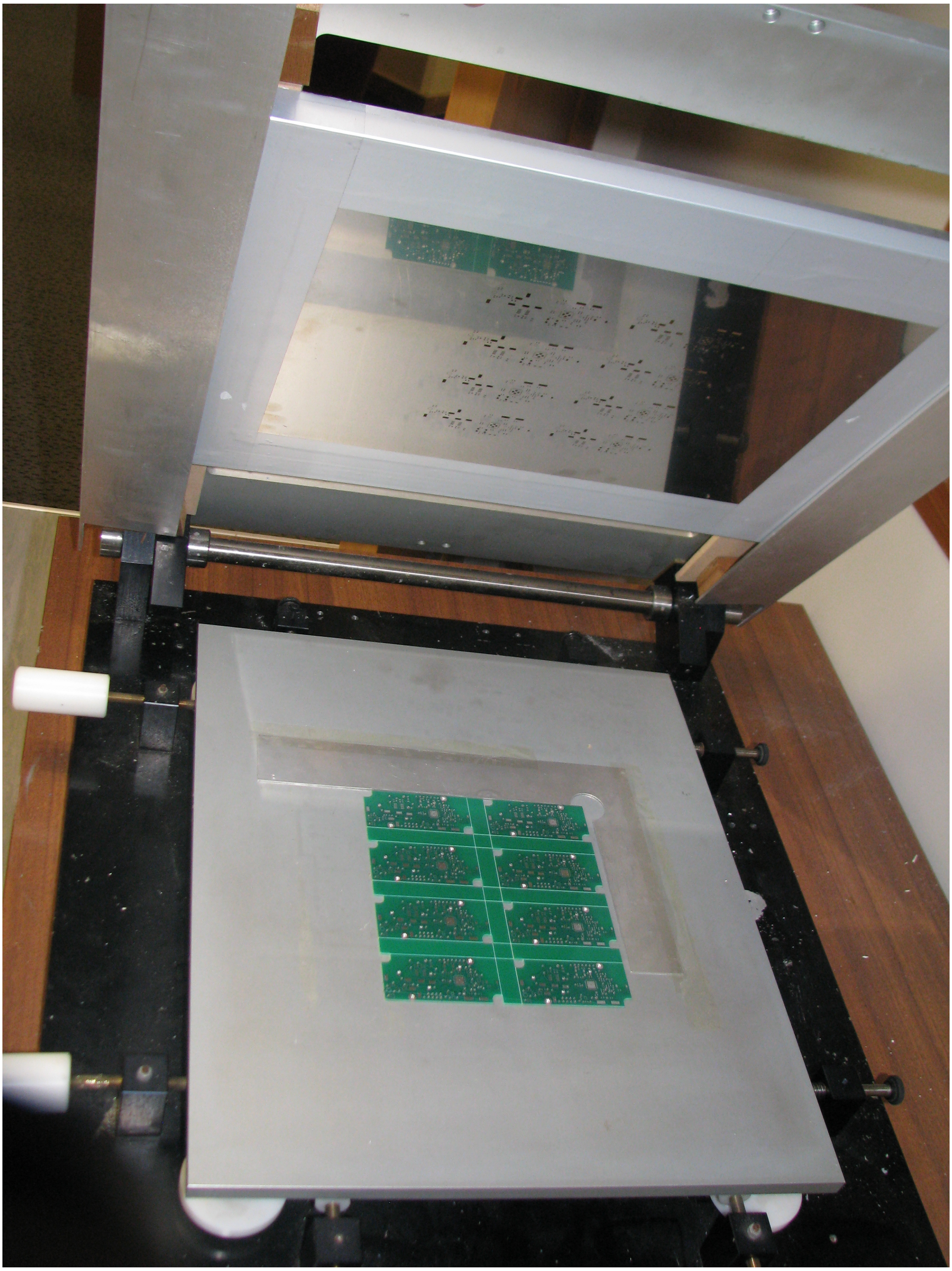


Figure 9.8: Solder stencil used to apply solder paste to boards.

$$V = IR \tag{9.1}$$

470 Ω and 10 Ω resistors were sufficent to create a measureable voltage drop across the resistor while maintaining sufficient supply voltage to the device for the normal and debug modes, respectively. The voltage was measured as a function of time with an oscilloscope. Figures 9.9 and 9.10 show the oscilloscope trace for the normal and debug modes, respectively. Excel charts with scales and linear approximations of the signal are overlaid on these figures. The linear approximations were used to integrate the current (calculated from Ohm's Law) over time.

When the device is in low power mode between compass readings in normal mode and radio intervals in debug mode, the devices use approximately 10 µA. During compass readings, the current spikes to 870 µA and decays over approximately 120 ms. With the compass reading interval set at 2 s, compass readings add approximately 15 µA to the average current. During radio intervals in debug mode, the current spikes up to 18 mA over 10 ms, adding 180 µA to the average current if the sleep time between radio polls is 600 ms and the radio polls are 4 ms long, which is the default setting. Shorter sleep times can be set if a faster response is desirable, for example when reading multiple flash pages, with a corresponding increase in power consumption.

At 27 µA average current draw, the devices will last for approximately nine months, not including flash page writes and wireless connections. If the battery voltage is too low to support radio operation when data is collected, a 3 V power supply such as an external battery pack can be connected to the programming/UART header to boost the power supply without losing data stored to RAM.

9.5 Internal resistance measurement

Batteries have an internal resistance comprised of electronic and ionic components[6]. The electronic component is used to describe the resistivity of all of the physical battery components; the ionic component describes the resistance for electrons to flow from one electrode to the other through the electrolyte. For a given battery configuration, the ionic component is a function of load, temperature, and remaining

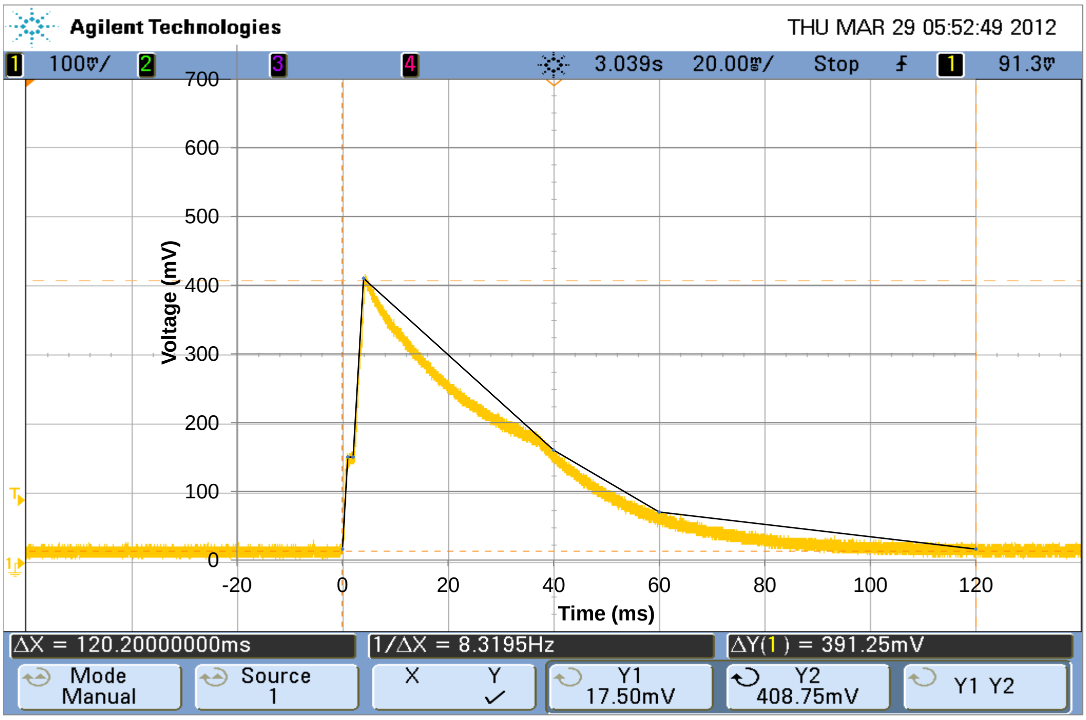


Figure 9.9: Voltage trace during normal mode operation.

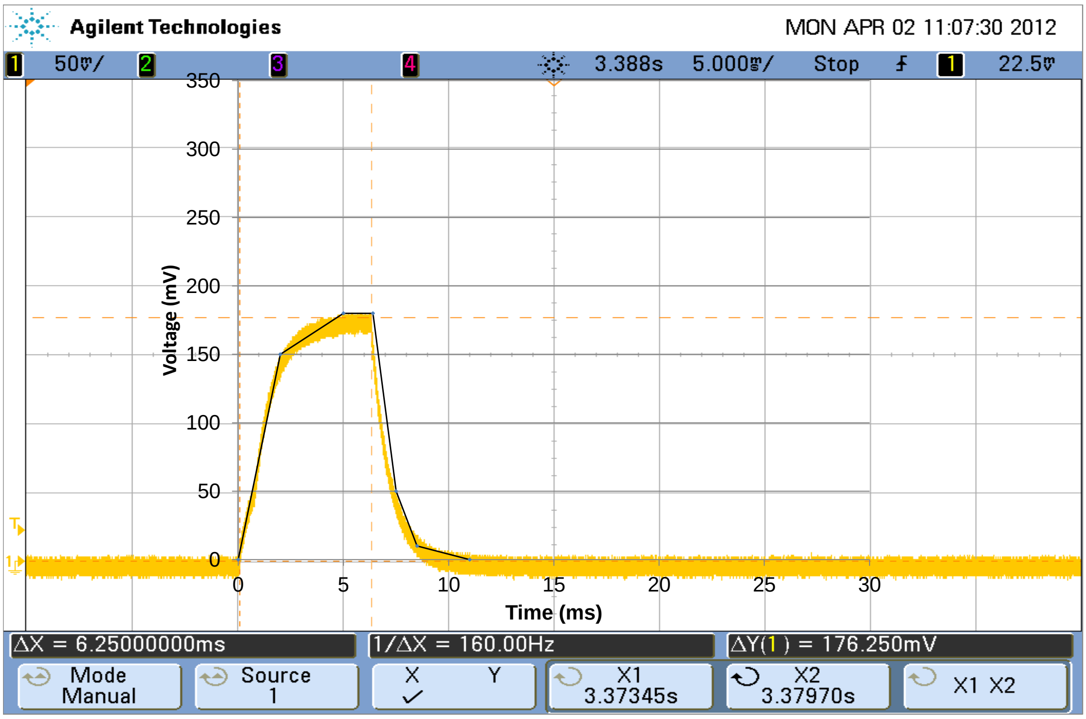


Figure 9.10: Voltage trace during debug mode operation.

capacity. The internal resistance decreases the voltage available to run connected circuit loads such as the door position logging devices. As the internal resistance is a function of remaining capacity, it was useful to calculate it to determine if the batteries running the door position logging devices exceeded their useful life. The devices were run at approximately constant temperature in indoor environments, so the change in internal resistance due to temperature changes was neglected.

Internal resistance can be approximated by measuring the voltage with a base load, applying an additional known current load, and measuring the change in voltage. The LED on the door position logging devices provided a convenient load on the devices which could be switched on and off and estimated. The battery internal resistance was estimated by dividing the change in voltage ΔV_{LED} when switching the LED on by the calculated current across the LED I_{LED}.

Current through the LED was calculated using the forward current characteristic obtained from the datasheet[7]. A fourth order polynomial shown in Figure 9.11 was used to interpolate the forward current as a function of forward voltage V_f. The supply V_s voltage for a given LED current was calculated by adding the voltage across the 150 Ω resistor in series with the LED to the LED forward voltage for that current.

Typically, the internal resistance of CR2032 coin cells slowly increases from approximately 10 Ω to 15 Ω over the first 100 mAh of capacity used, and then begins rising rapidly[8]. The 18 mA pulse during debug mode will cause a reduction in supply voltage of approximately .5 V once the battery internal resistance reaches 30 Ω, at which point the supply voltage may drop below the minimum of 2.3 V required for accessing the flash. The trend in calculated battery internal resistance and LED off voltage for four devices over a period of approximately nine months is shown in Figure 9.13.

As expected, the battery internal resistance was still below the 30 Ω after nine months of operation, although it had begun rising rapidly. Also, the battery internal resistance was a better measure of remaining battery capacity than battery voltage because internal resistance gradually increased as the battery was being consumed, unlike the voltage which remained essentially constant until the battery reached the end of its life.

The devices may run in normal mode up to much higher battery internal resistance because the maximum current is approximately 0.9 mA for a shorter time.

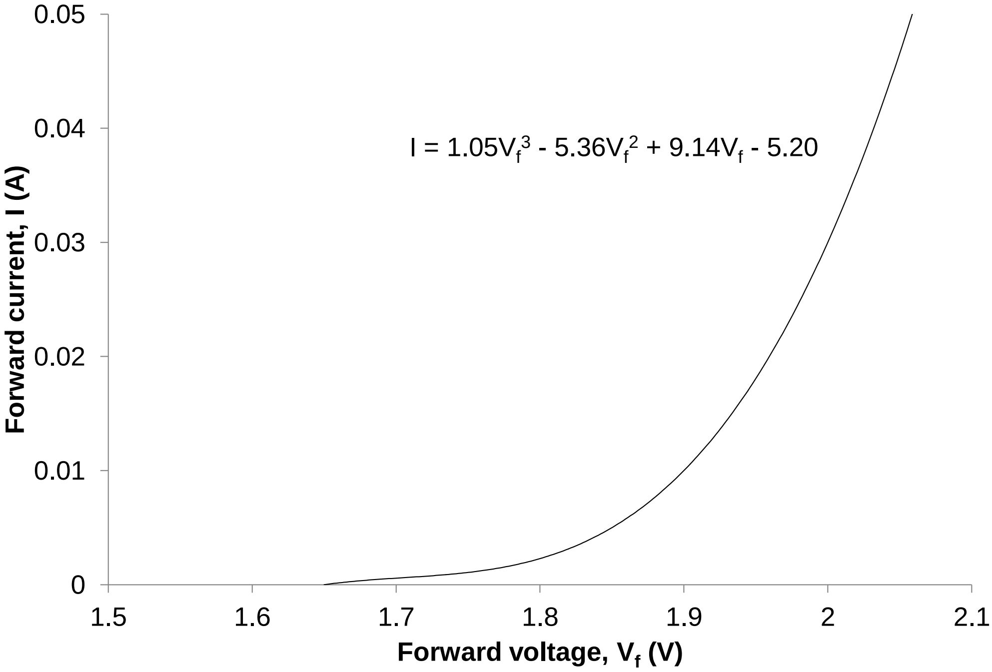


Figure 9.11: Forward current as a function of forward voltage for the LED, obtained from the datasheet[7].

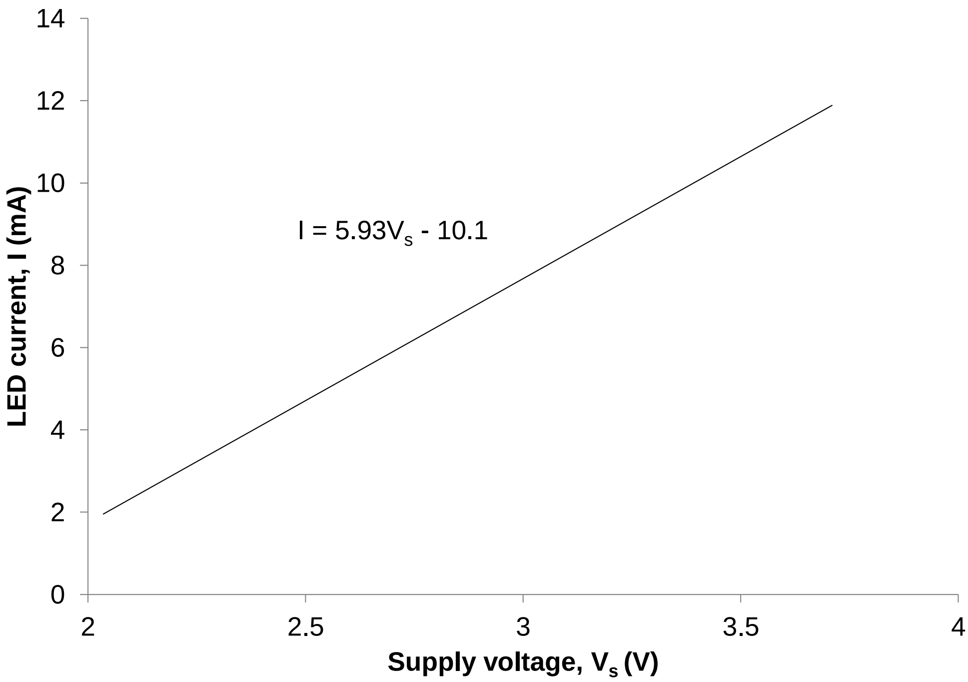


Figure 9.12: LED current as a function of supply voltage for the LED in series with the 150 Ω resistor, approximated as a linear relationship.

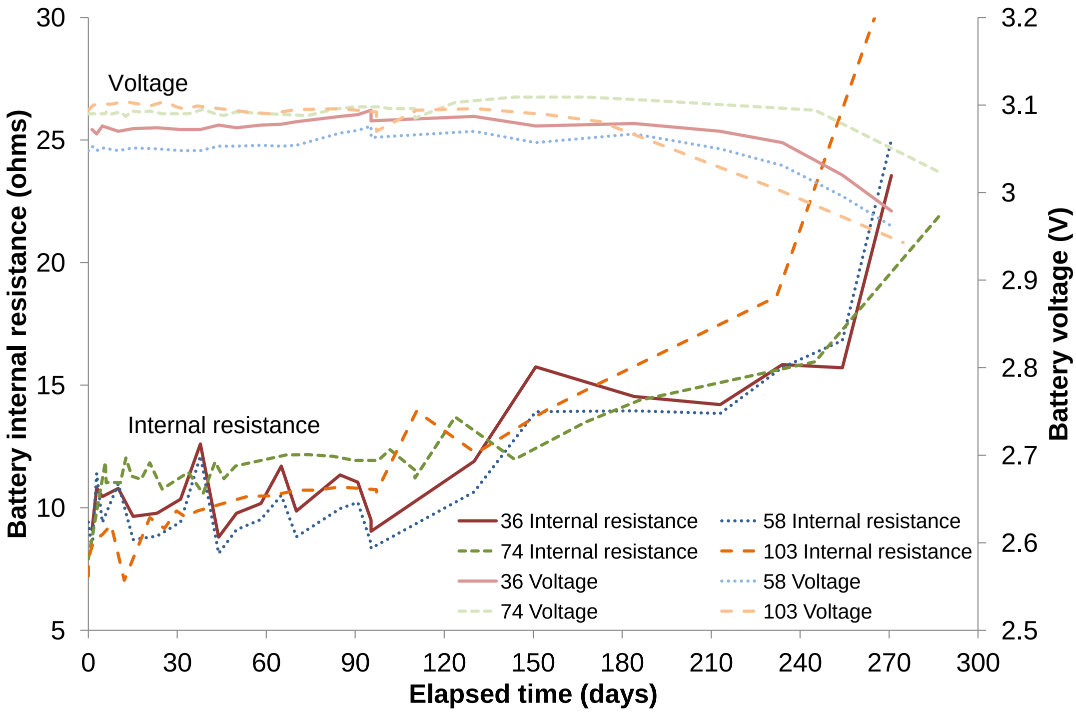


Figure 9.13: The battery voltage and internal resistance characteristics for four devices over an operational period of approximately nine months.

A 3 V regulated USB power supply was used to boost the supply voltage to transfer data if the battery was too weak to access the flash with the radio active, which was the scenario with maximum current draw.

9.6 Magnetometer testing

As previously stated, magnetometer output can be influenced by nearby objects such as ferromagnetic material or electronic equipment. Typical effects have been described as "hard iron" where a constant magnetic field is added to the geomagnetic field by a proximal ferromagnetic material and "soft iron" where a nearby magnetic material distorts the geomagnetic field [9]. Hard and soft iron effects are observed in magnetometer output by a shift or distortion, respectively. Seven of the devices were randomly selected and tested on the E329 door of the Civil/Mechanical Engineering Building at the University of Canterbury in the positions shown in Figure 9.14. Device 60 was tested with single and dual battery configurations to characterise the effect of a battery adjacent to the compass, shown in Figure 9.16. The battery was noted to shift the magnetic field measured in both the x and z directions. A function to offset individual magnetometer axis output by a constant amount for the angle calculation was added to compensate for this behaviour.

The magnetic field measured at each device location on the door was stable with time but it varied between locations on the door. As a result, a calibration procedure was developed where ten compass samples were taken from the door fully closed position to the fully open position before and after data collection. Mounting positions near the hinge were observed to provide a more consistent magnetic field, represented by a monotonically changing elliptical output from the magnetometers over the door travel path, likely due to the reduced travel of the magnetometer relative to magnetic field affecting objects nearby. As the optimal position for accelerometer output was as far from the hinge as possible to amplify the acceleration of the device, balancing the location to provide acceptable output from the two sensors was difficult.

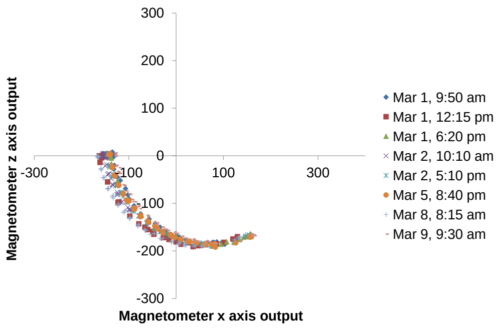
9.7 Magnetometer angle calculation

The measured x, y, and z components of the magnetic field are shown graphically in Figure 9.17. Assuming the magnetic field remains constant as the compass rotates in the x-z plane, the y component remains constant and the measured x and z values reflect the angle of the door to the magnetic field. As directly recording the raw data was memory intensive, 16 discrete door opening angles were calculated to reduce the memory requirement for each door position to four bits. Three options were evaluated for measuring the change in door angle $\Delta\theta$ which is equal to the difference of the door angle to the magnetic field at an open position $\theta_{m,2}$ and the closed position $\theta_{m,1}$. An approach described in a Honeywell application note[10] calculates the angle Θ at each position as follows:

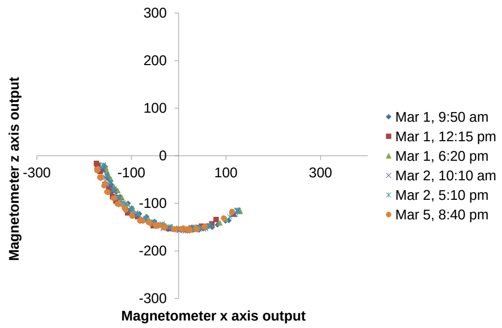
$$\Delta\theta = tan^{-1}\frac{m_{x,2}}{m_{z,2}} - tan^{-1}\frac{m_{x,1}}{m_{z,1}} \tag{9.2}$$

However this method provides negative output for clockwise door motion, and some logic would be required to handle angles passing 360^o. This method would not be able to handle the complex magnetic field behaviour noted when the devices were mounted away from the hinge on the E329 door.

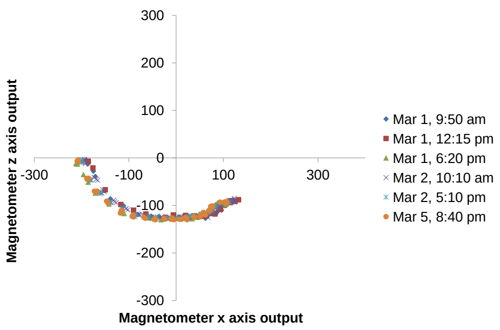
Figure 9.14: Magnetometer output testing on E329 door; device numbers are shown.



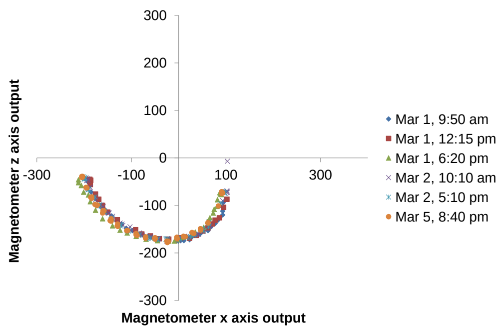
(a) Device 4



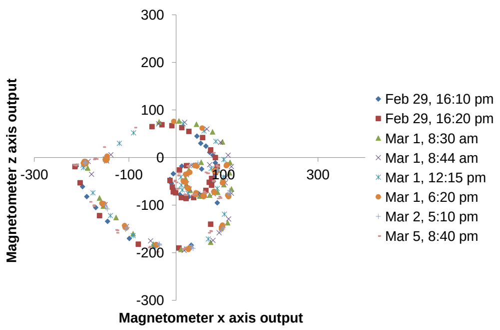
(b) Device 8



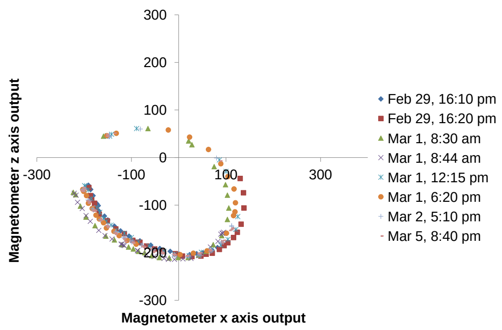
(c) Device 44



(d) Device 57



(e) Device 65



(f) Device 68

Figure 9.15: Magnetometer raw output for devices 4, 8, 44, 57, 65, and 68 when mounted on door E329.

A method that would be able to handle complex magnetic field behaviour would be to use a lookup table calibrated for specific door positions. However, this

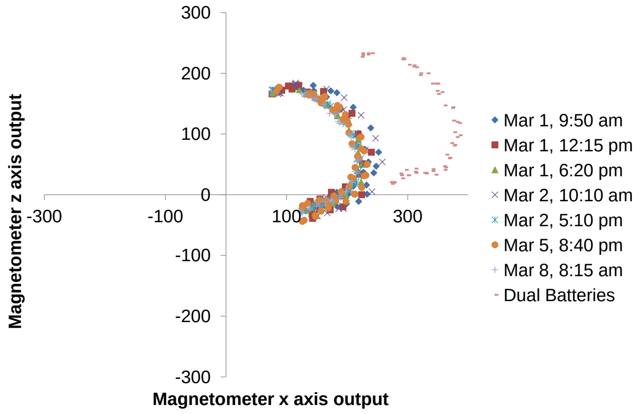


Figure 9.16: Magnetometer raw output for device 60, mounted on E329 with single and dual battery configurations. The close proximity of the second battery to the magnetometer shifted the output of the x and z axes (an example of a hard iron effect).

approach would require a more accurate calibration procedure which would not be time efficient.

The third method considered was to use the dot product of the measured magnetic field vectors to calculate the angle as follows:

$$\Delta\Theta = cos^{-1}\frac{\mathbf{m_1} \bullet \mathbf{m_2}}{|\mathbf{m_1}|\,|\mathbf{m_2}|} \tag{9.3}$$

which had the advantage over the tangent method of always providing a positive angle from the reference vector (in this case, corresponding to the door shut position). A discrete door angle data point was obtained by dividing the calculated angle by the angle calculated for a fully open door (90^o), resulting in 16 data points from 0^o (door shut, position 0) to 90^o (door fully open, position 15). Any door opening angle past 90^o was recorded as 90^o. This method was selected for the final design.

When the devices were initially installed on a door, positive and negative magnetometer self tests were run. The self test imposed an internally generated magnetic field on each axis and recorded the change in output which indicated if the magnetometer was operating properly, as described in the magnetometer

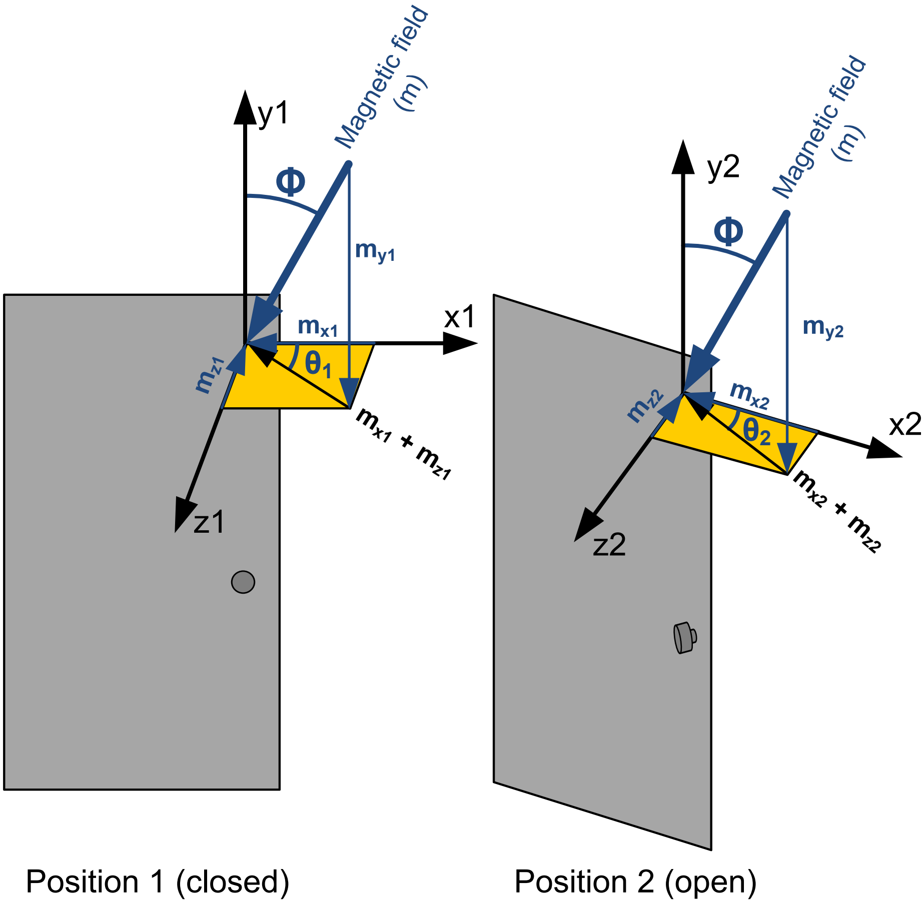


Figure 9.17: Conversion of compass raw output to angle. The compass provides x, y, and z magnetic field magnitude output, which can be converted into an angle by a variety of means.

datasheet[2]. An initial test sequence was subsequently conducted by recording 10 data points through the range of motion of the door. To improve the accuracy of the angle calculation by compensating for hard iron effects, a circle was fit to this data using the least squares method described by Bullock[11]. The output was then shifted so the output was centered at zero for both x and z axes, as shown in Figure 9.18. A second set of 10 data points was then taken to establish the calibrated output of the magnetometer. Soft iron effects were evaluated by considering the fit of the circle and the shifted output compared to radial lines drawn in 10^o increments to 90^o in both directions. After data collection, a final set of data points was taken over the full door motion to determine if the magnetometer output had remained stable over the data collection period.

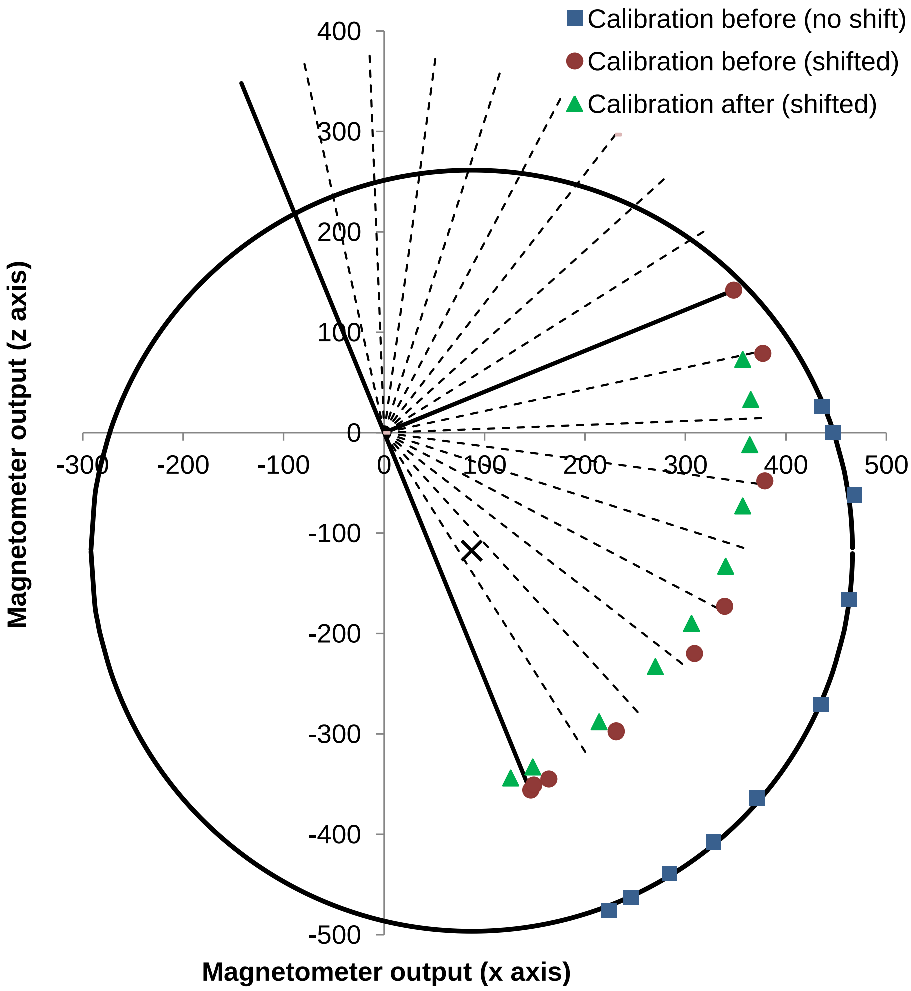


Figure 9.18: Magnetometer field calibration procedure. A circle was fit to raw magnetometer output with the least squares method described by Bullock[11]. The center of the circle is marked on the figure with an X. The magnetometer output was then shifted to center the circle on the origin. Lines incremented by 10^o radially from the door closed measurement to 90^o in both directions were plotted to identify if soft iron effects were significant. Note: the calibration performed after data collection did not start at 0 as the door was kept slightly ajar to prevent locking the author in the stairwell.

To conserve memory, door position data was only recorded if the measured position of the door changed. It was observed that if the door was in a position where the measured magnetic field was near the transition between two calculated discrete angles additional "noise" data points were recorded, as shown in Figure 9.19. To address this issue, the door position was calculated in 32 increments and only recorded if it changed by an absolute increment of greater than 1. The value recorded was then the calculated position divided by 2.

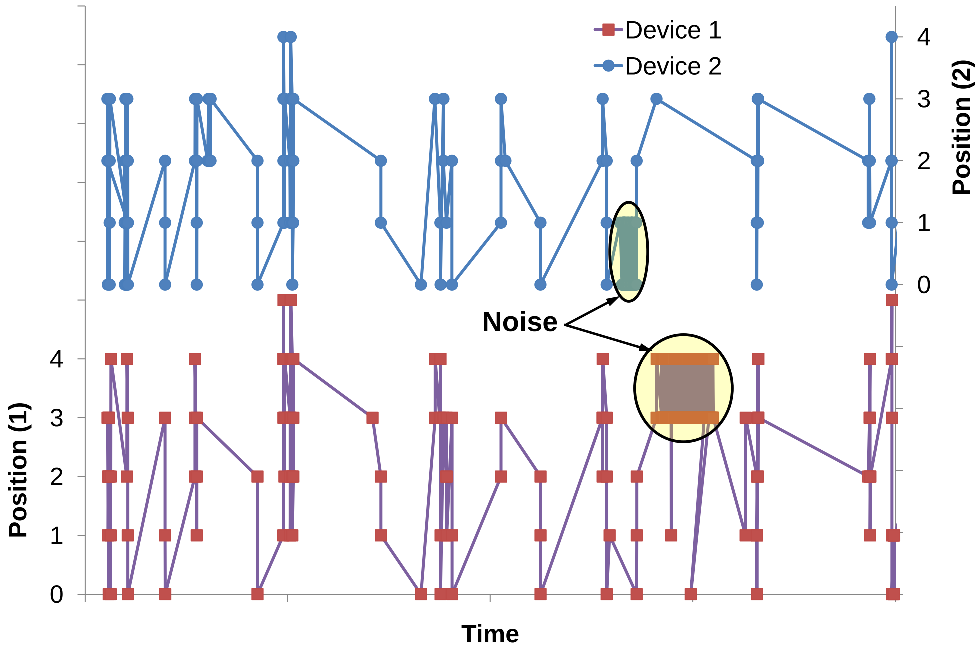


Figure 9.19: Noise observed in door position recorded data. For this data, angles of 4 and 5 represented a fully open door for devices 1 and 2, respectively.

9.8 Data storage

In order to compress the data storage requirements for each recorded sample, three data types were used: position data, 15 minute time recordings, and daily time recordings. Each data point was limited to a 16 bit word. Two bits were used to indicate the type of data stored. For the position data, 4 bits were consumed with the door position. The remaining 10 bits were used for a time stamp with one second resolution. If a sample was taken in the preceding 15 minutes, a 15 minute time stamp was recorded to indicate that the preceeding values had been recorded during that 15 minute interval of the day. At midnight the day and month were recorded, followed by a 12 bit battery voltage reading. The data storage scheme for all the above types of data except the battery voltage reading are shown graphically in Figure 9.20.

The 4 Mbit flash memory was split into 2,048 256 byte (128 word) pages. The first page was reserved for storing the total number of flash pages used and other calibration data if required, leaving 2,047 pages capable of storing 128 words each, or 262,016 potential data points. Based on 180 days of testing per device, 360 data points are consumed with midnight and battery data storage. Assuming 100% of the 15 minute intervals were recorded, another 17,280 data points were required, leaving 244,376 points for door position data, or a maximum average of 1,357 door position data points per day. Assuming that the average door opening event took 6 s or consumed an average of three data points, an average of 450 door movement events per day could be captured using the devices over the 180 day testing period.

As the flash memory was non-volatile, the maximum amount of data that could be lost in the event of a power disruption or microcontroller reset was the contents of the RAM, a maximum of 128 data points if the RAM was completely full. A microcontroller reset could be identified in the data because the first flash page recorded after a reset would have the reset date (January 1, 2000) recorded as the first value.

9.9 Real time clock drift correction

The 32.768 kHz crystal oscillators specified have a frequency tolerance of $\pm$20 ppm at 25^{o}C, which corresponds to a microcontroller clock accuracy of $\pm$2 s per day, or $\pm$6 minutes over the intended 6 month data acquisition period. The crystal has a minimum temperature frequency coefficient β of -.04ppm/T^2, so a change of 10^{o}C can cause the frequency to change by approximately 4 ppm[12]. The interior ambient temperature in the buildings monitored would not be expected to vary by more than 10^{o}C to 30^{o}C. The laptop clock was synchronised with the NIST Internet Time Service time.nist.gov, and the device clock was initially synchronised with the laptop time at t_o. The time drift of device 74 was tracked over 45 days while installed on the E329 door, shown in Figure 9.21.

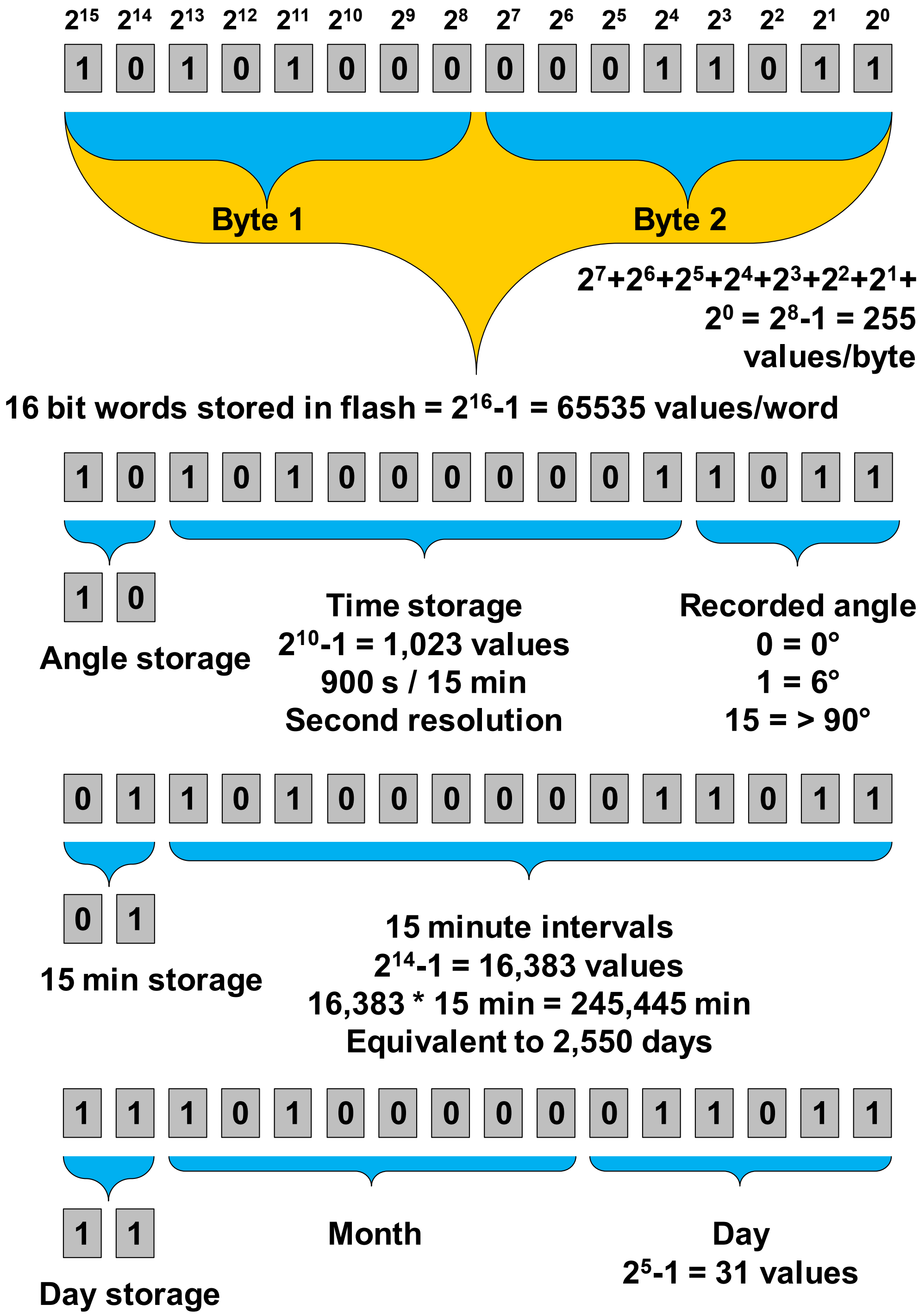


Figure 9.20: Data storage scheme for door position, 15 minute, and month/day data types.

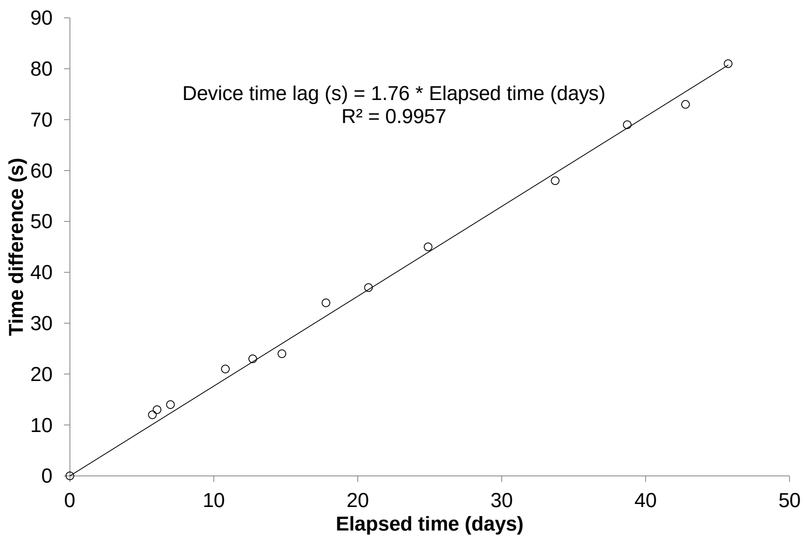


Figure 9.21: The time drift measured for device 74 when mounted on E329 over a period of 45 days.

The temperature in E329 was not tracked during this time, but it was noted to fluctuate as expected in a typical office environment. The time drift remained essentially linear during the measurement period, so the time drift during field data collection was assumed to be linear as well as only two points were recorded, prior and after data collection. When data was collected at t_r, the clock error ϵ_t was estimated by the following equation:

$$\epsilon_t = \frac{t_{device,r} - t_o}{t_{laptop,r} - t_o} \tag{9.4}$$

Sample times were then corrected with the following equation:

$$t_{sample,corrected} = \frac{t_{sample,recorded} - t_o}{1 - \epsilon_t} + t_o \tag{9.5}$$

9.10 Future improvements

As previously noted, the accelerometer does not provide a reduction in power consumption for long term data collection where high time resolution is not required.

The accelerometer could be removed for a cost savings, or a mechanical low pass filter mounting system could be designed to get more use out of the accelerometer.

At the time of writing it took approximately 10 minutes to transfer the full flash memory to a PC when running the RF bridge at 12 MHz, the UART at 460.8 kbps and with a 100 ms radio poll sleep time. This was improved from approximately 1 hour when running the RF bridge at the standard 1 MHz frequency which limited the UART transmission rate to 115.2 kbps and a 600 ms radio poll sleep time. The transmission protocol could be optimised to reduce flash data transfer. Clocking the door mounted device and flash SPI connection up may also reduce the flash read time.

When reading over 500 pages of flash memory, pages would occasionally fail to transit. An improved data transmission protocol with error checking could be implemented to improve the reliability of data downloading from the devices.

The expansion header installed on the devices allows additional sensors to be connected. Data on other types of passive compartmentalisation features, such as position of windows, could be collected by adding a different type of sensor. Hinged window position could be logged with the devices in their current hardware configuration; awning (hinged on top) window position could be logged with the accelerometer and casement (hinged on the side) window position could be logged with the compass. Logging the position of sliding windows would require a method of measuring distance such as a linear displacement or ultrasonic distance sensor.

9.11 Door reliability data collection

9.11.1 Trial evacuation data collection

During evacuations, doors will be open while occupants pass through them. While this dissertation does not focus on human behaviour, the spread of fire products may be affected by doors opened by egressing occupants. Boyce et al. has collected data on the time it takes for people to negotiate doors with a door closing force ranging from 21 N to 70 N at levels of disablement ranging from no aids to walking frames required, in both push and pull directions[13]. The mean negotiation time ranged

Door description	Hold open device	Width (mm)	Half width (mm)	Effective width (mm)	Opening force: Left (N)	Right (N)
Back E11	No	800	N/A	500	22	N/A
Level 3	Yes	900	N/A	600	18	N/A
Comp. lab	No	1500	750	1200	67	54
near E11	No	1700	850	1400	45	156
Outside (Civ/Mec)	No	1800	900	1500	31	31
EPS Library	No	1800	900	1500	45	45
Glade doors to Civ/Mec	No			No data		
Covered Walkway doors	No			No data		

Table 9.2: Doors monitored during Civil/Mechanical and EPS library trial evacuations.

from 3 s for people requiring no aid at a closing force of 21 N for a push door to 9 s for people with a walking frame and a pull door with a closing force of 60 N. C/VM2 specifies that modelled door opening times shall be 3 s per occupant in low occupant density conditions and the queuing time in high occupant density conditions when queuing is expected[14]. Data on door opening times during trial evacuations of the Civil/Mechanical Engineering and Engineering and Physical Sciences (EPS) Library buildings was collected by video to evaluate the egress door opening times specified in C/VM2. During the Civil/Mechanical Engineering building evacuation, the door position data loggers were used simultaneously with video recordings to verify the operation of the devices.

The doors selected for monitoring included a range of widths, leaf configurations, hold open devices, and locations. Table 9.2 lists the characteristics of the doors monitored by video during the evacuation. For two of the doors, no egress traffic was observed. Door opening forces were measured at the initial point of opening by a spring scale.

The door position measured by the logging devices successfully corresponded with the video recorded data. Typical data for single and multiple occupants evacuating is shown in Figure 9.22. It was noted during the time that the devices were mounted on the door that some individuals noticed their presence and some devices showed evidence that they had been removed and replaced on the door. If the devices were not replaced in the same orientation as originally mounted, the recorded data was adversely affected. As a result, a “DO NOT REMOVE” label and a second label with directions to contact the author and contact information were affixed to the front and rear of the devices, respectively. Also, magnetometer calibrations from before and after data collection were compared, and the mounting positions were photographed to determine if the devices had been moved during the data collection period.

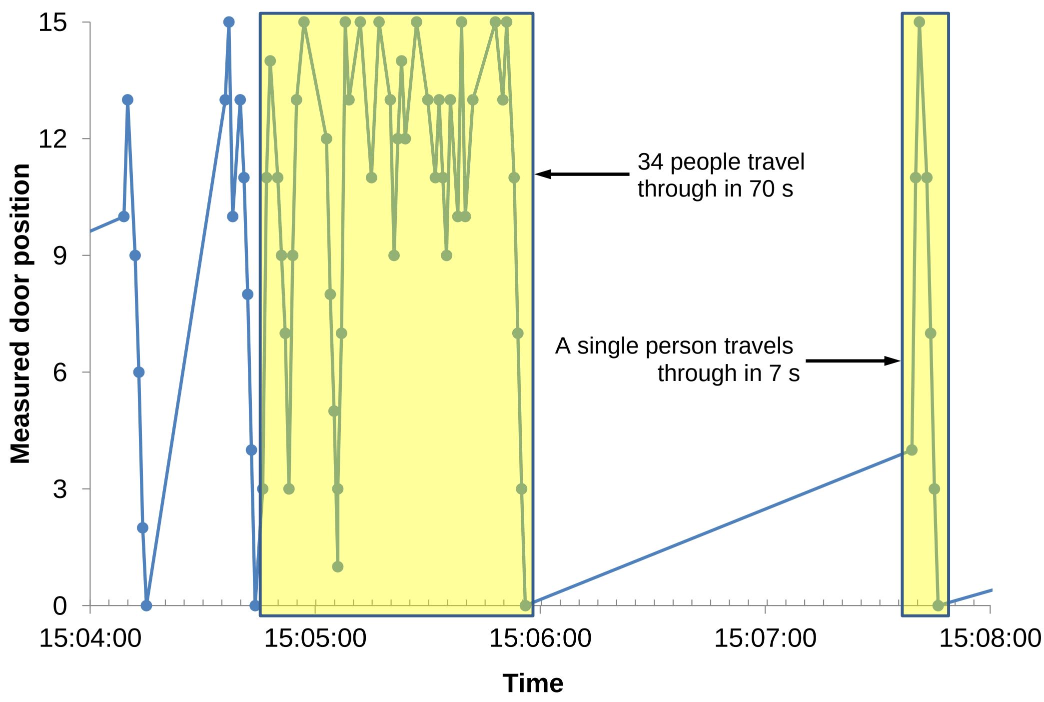


Figure 9.22: Typical evacuation door position data, showing the door changing position as multiple occupants in a single queue and a single occupant exit the University of Canterbury Civil/Mechanical Engineering Building.

A histogram of the times recorded to the nearest second for door negotiation by single occupants (the time between the door states of being completely closed) is shown in Figure 9.23. Door negotiation times ranged from 3 s to 7 s for the 17 instances where a single person passing through a door was observed.

There were 15 instances where more than two people were observed exiting in a continuous stream. The maximum number of people in one stream was 37. There were 12 instances of continuous streams of people egressing at locations where double door leaves were available, but in only five instances were both leaves used. In one instance where both leaves were used, one of the egressing persons used an object to block one of the leaves open. Building staff were observed holding double leaves open to facilitate egress, but they were the last occupants leaving so it did not affect the egress. However, this behaviour did result in open doors for a longer duration. In the computer lab, several occupants were noted entering the room in the opposite direction of the egress path, presumably to retrieve personal belongings.

The queuing time was calculated using the method described in C/VM2[14]:

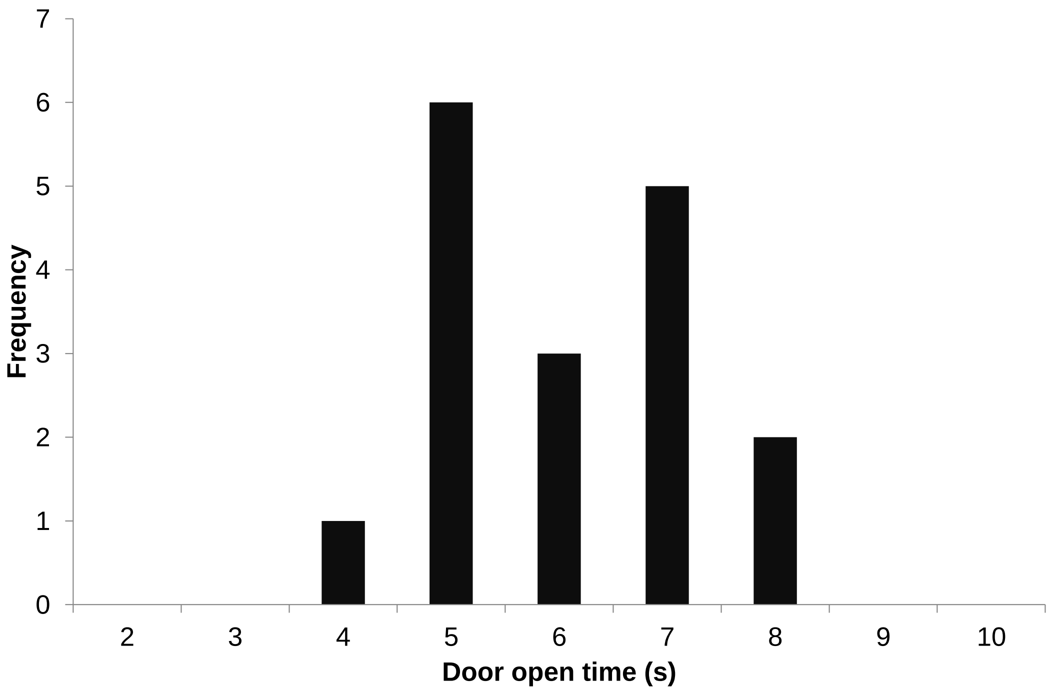


Figure 9.23: Measured door negotiation time for single persons in a trial evacuation of the University of Canterbury Civil/Mechanical Engineering Building.

$$F_c = (1 - a \cdot D)k \cdot D \cdot W_e \tag{9.6}$$

Where F_c is the specific flow in persons/s, a and k are determined from the table listed in C/VM2, D is the occupant density (C/VM2 recommends 1.9 persons/m^2 near door restrictions), and W_e is the effective width of the door (two boundary layers of 0.15 m subtracted from the width of the door opening, as recommended in C/VM2). The measured times were compared to the calculated queuing time and also the three seconds per occupant assumption, shown in Figure 9.24. The actual times were found to lie between the two methods for the majority of cases; the queuing time calculation was not conservative and estimated times were shorter than measured and using three seconds per occupant was conservative with times estimated to be longer than measured. The likely cause was that since the occupants were not truly "queued" and were moving in a steady stream, yet travelling close enough that the door was not allowed to completely close in between occupants negotiating the door.

This information may be useful for future versions of BRISK if an evacuation

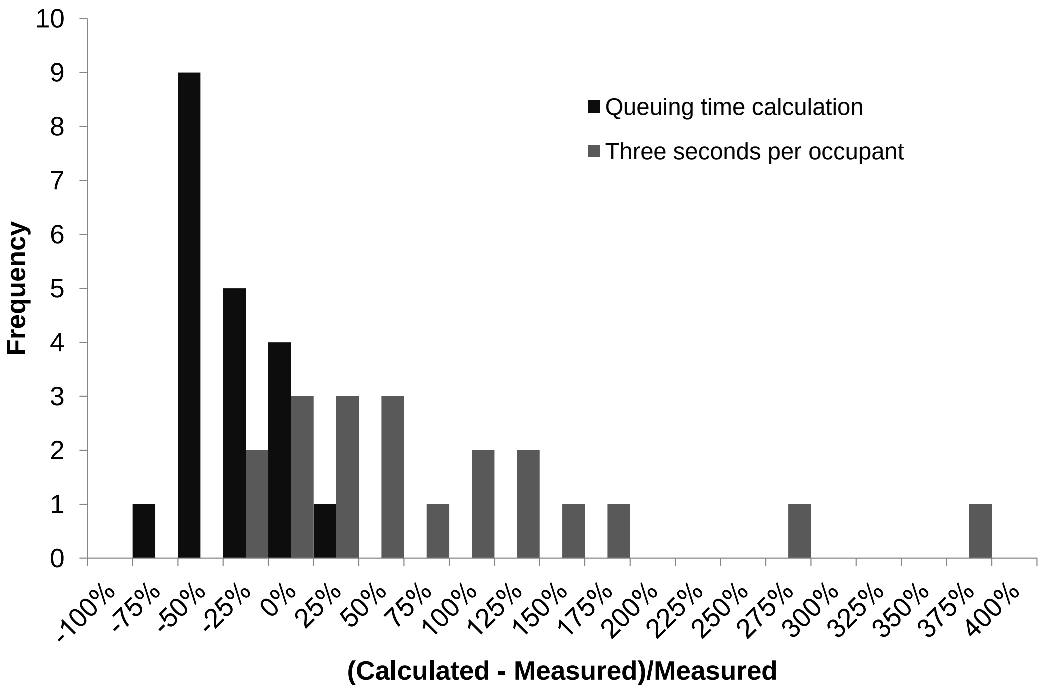


Figure 9.24: Comparison of measured door negotiation time for multiple occupants to queuing time calculation and three seconds per occupant in a trial evacuation of the University of Canterbury Civil/Mechanical Engineering Building.

model is integrated.

9.11.2 Long term door reliability data collection

9.11.2.1 Building and door selection

In New Zealand, building inspections are completed as part of the annual Building Warrant of Fitness requirements by an Independently Qualified Person (IQP) or Licensed Building Practitioner (LBP)[15]. The requirements for inspection of specified systems including those that relate to means of escape from fire are set out in a document known as a Compliance Schedule. Specified systems for escape from fire include electromagnetic or automatic doors or windows[16].

Doors were identified for monitoring through the assistance of Fire Fighting Pacific, a company based in Christchurch that designs, installs, and services fire

Type of building	Number of buildings	Number of door leaves
Hotel/backpackers	6	32
Apartment/condo	2	5
Boarding house/dorm	2	7
Rest home	3	8
Total	**13**	**52**

Table 9.3: A summary of the building types and number of doors studied.

protection systems, and also provides inspection services for Building Warrant of Fitness purposes. The scope of the study was limited to buildings with sleeping occupancy, because open doors are most likely to have an adverse effect on life safety for sleeping people. Doors were selected in buildings in the Christchurch and North Canterbury areas. A list of the building types and number of door leaves monitored in each type of building is shown in Table 9.3.

The selected doors were 0.8 m to 1.0 m wide hinged fire or smoke control doors that formed part of the shared means of escape for the buildings; single household unit doors were not included. Of the doors considered, nine had fire door signage, ten had smoke control door signage, and 33 did not have visible signage indicating the type of door. With the exception of two doors, doors with self-closers only (no approved hold-open devices) were selected because the door logging devices could not differentiate whether the hold-open device was operating properly or not. This does not mean that hold-open devices do not fail. Anecdotal evidence from Fire Fighting Pacific indicated that doors with hold-open devices had been observed to fail due to lifted carpets or objects placed in the path of the door swing. It is also possible for a hold-open device to fail due to a malfunctioning detection system. During the door selection process it was noted that the majority of shared means of escape doors in sleeping occupancies in the Fire Fighting Pacific building population did have approved hold-open devices, limiting the potential population of doors for the study. Two doors with hold-open devices were included for comparison.

Door failures were noted during the deployment of the devices; four examples are shown in Figure 9.25. The majority of the failures were propped open doors; additionally, a single door was found with a disconnected closer. It was noted anecdotally that double sets of doors such as shown in Figure 9.25(b) were propped open as readily as single doors.

(a) Propped open (b) Wedged open x 2

(c) Propped open (d) Disconnected closer

Figure 9.25: Door failures noted during door study.

9.11.2.2 Results

To distill the 16 position door output data into a single summary figure for the probability that a door was open at any time, the time that each door was positioned at the “2” or greater position was summed and divided by the total data collection time. The probability distribution for the fraction of time that a door was open is shown in Figure 9.26. The best-fit distribution was an Inverse Gaussian with mean μ = 0.104 and shape factor λ = 0.0117. The Kolmogorov-Smirnov value for this distribution was 0.118. This distribution was highly skewed to the left, indicating that the majority of doors were closed most of the time with a few that were propped open for large periods of time. The probability for each individual door to be at each position is shown in Appendix C.

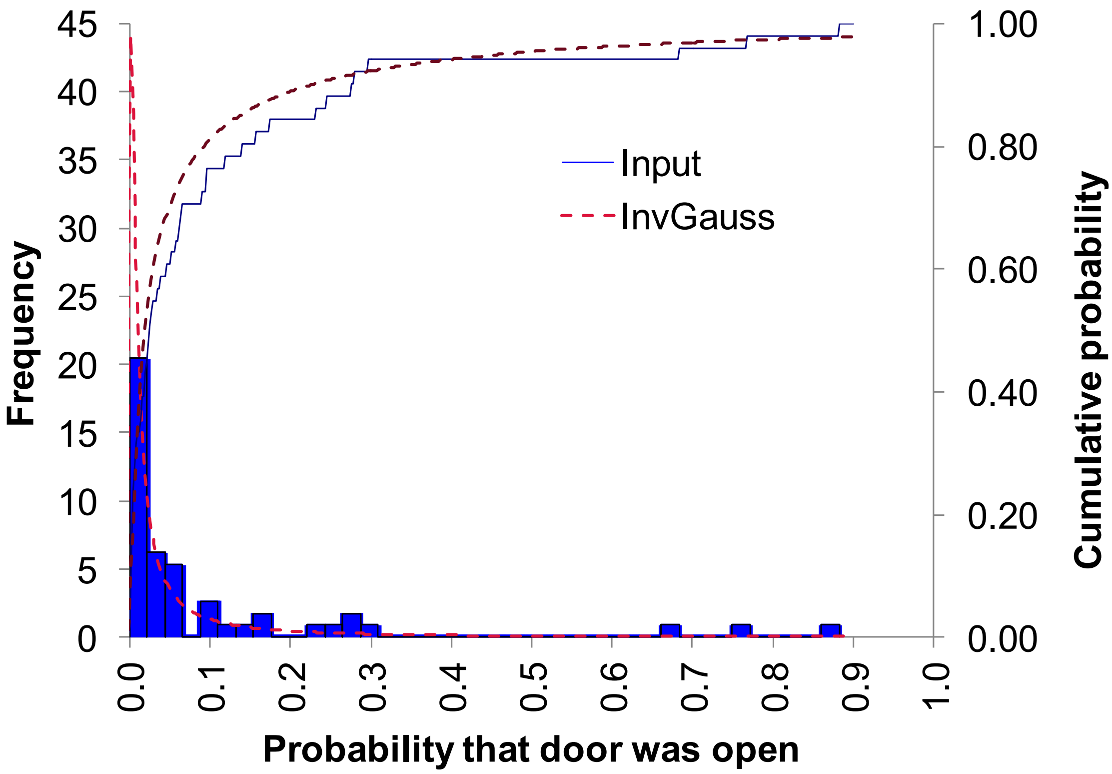


Figure 9.26: The overall probability of a door being open from the 52 door sample, collected over six months.

Summary statistics for door reliability for each type of building and the total population are shown in Table 9.4. Doors in the rest homes had the highest reliability and the least uncertainty, followed by the hotel/backpackers, apartment/condos, and boarding house/dormitories.

The collected data was split into nominal working hours from 0800 h to 1700 h and non-working hours from 1701 h to 759 h to determine if there was an effect on the probability that a door was open or closed, shown in Table 9.5. There was a higher probability that a door was closed in the hotel/backpackers occupancy during non-working hours. A likely cause for this change was the use of the doors by cleaning staff during working hours. Otherwise, there was very little difference be-

Type of building	Mean	St. dev.
Rest home	0.95	0.05
Hotel/backpackers	0.90	0.16
Apartment/condo	0.86	0.30
Boarding house/dorm	0.85	0.32
Total	0.90	0.19

Table 9.4: Summary statistics for the overall door reliability for the 52 door sample.

tween working and non-working hours. The probability that each individual door was closed at each hour of day is shown in Appendix C.

	0800 to 1700		1701 to 0759	
Type of building	Mean	St. dev.	Mean	St. dev.
Rest home	0.95	0.05	0.95	0.05
Hotel/backpackers	0.88	0.17	0.91	0.15
Apartment/condo	0.86	0.30	0.86	0.30
Boarding house/dorm	0.85	0.32	0.85	0.32
Total	0.89	0.20	0.90	0.19

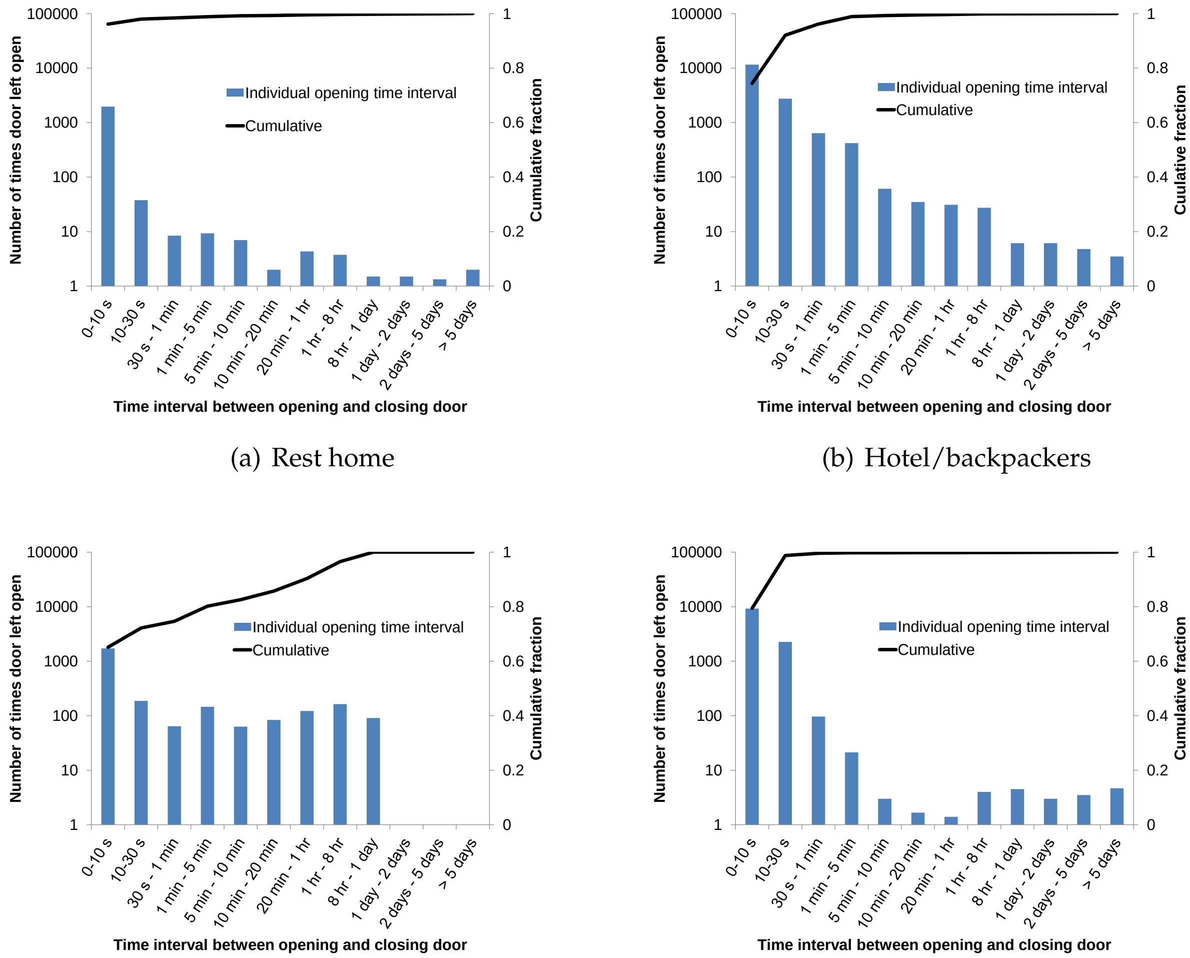
Table 9.5: Summary statistics comparing working and non-working hours for the 52 door sample.

The data was also split into weekend days and weekdays, shown in Table 9.6. Again, there was very little difference other than a slight increase in the probability that doors were closed for the hotel/backpackers building type during the week, which likely reflects a lower usage of these types of buildings on weekdays.

	Weekend		Weekday	
Type of building	Mean	St. dev.	Mean	St. dev.
Rest home	0.95	0.06	0.95	0.05
Hotel/backpackers	0.89	0.16	0.90	0.16
Apartment/condo	0.86	0.30	0.86	0.30
Boarding house/dorm	0.85	0.33	0.85	0.32
Total	0.89	0.19	0.90	0.19

Table 9.6: Summary statistics comparing weekend and weekday probabilities that doors were closed for the 52 door sample.

The probability that the 52 doors were closed was found to be higher than the 1970 UK study[17] discussed in Chapter 8, which found 17% of dwelling doors (compare to probability of 0.86 for doors in apartment/condo buildings in this study to be closed), 23% of school doors (compare to 0.85 probability for boarding house/dorm



(a) Rest home

(b) Hotel/backpackers

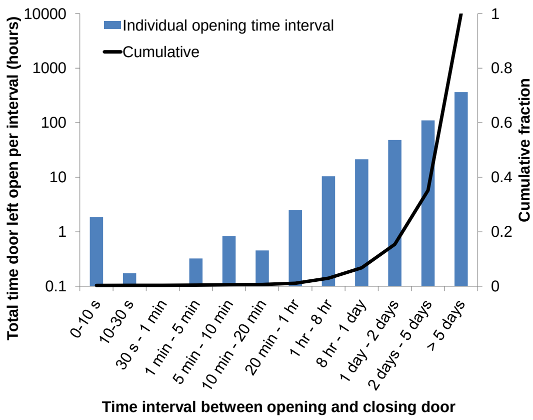
(c) Apartment/condo

(d) Boarding house/dorm

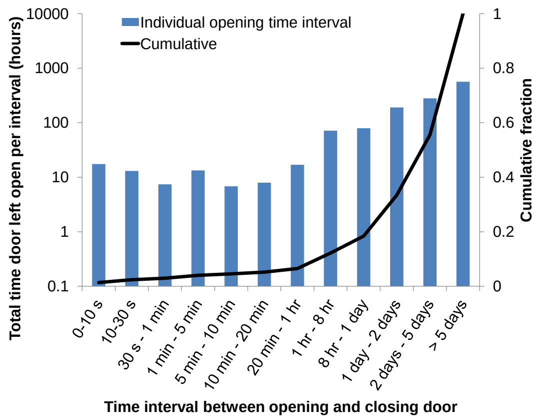
Figure 9.27: The mean number of times that doors were opened by open/close time interval.

doors to be closed in this study), and 39% of institutional doors (compare to 0.95 probability for rest home doors to be closed in this study) to be propped open.

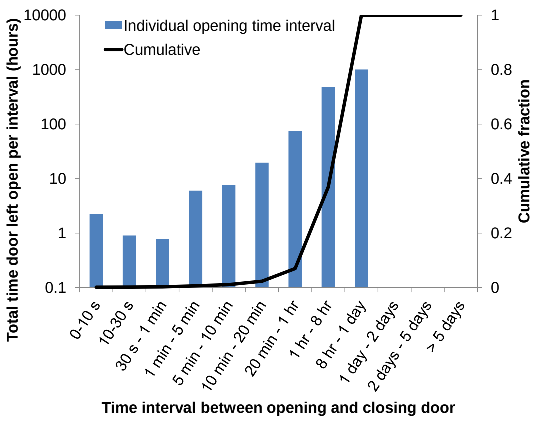
The mean number of times that doors were opened for specified time intervals and the cumulative amount of time that the door was open when opened for those specific time intervals are shown in Figs 9.27 and 9.28, respectively. The total number of times that doors were opened ranged from 74 to 51,760 over the test period. While doors were opened and closed within short periods of time much more frequently, longer door-open times contributed more to the total amount of time that the doors were open. This shows that normal use of the doors where they are open for short periods of time did not have a large impact on the overall performance of the doors. All of the occupancies had doors that were left open for longer than one



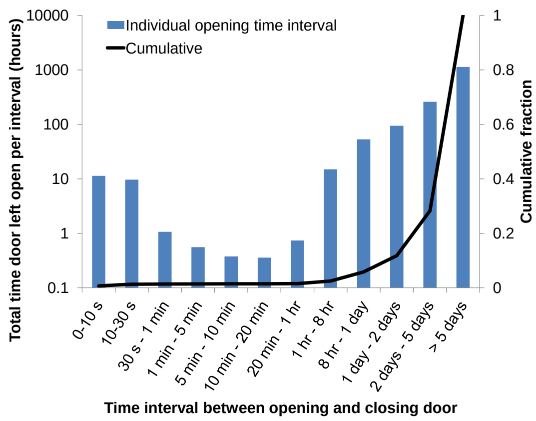
(a) Rest home



(b) Hotel/backpackers



(c) Apartment/condo



(d) Boarding house/dorm

Figure 9.28: The mean cumulative time that doors were left open when cycled from open to closed for the specified intervals of time.

day with the exception of the apartment/condo buildings, which may be a result of the emphasis for overnight security in these buildings.

The influence of a form of the *"Hawthorne Effect"* can not be ruled out on the results. The Hawthorne Effect describes the potential for human behaviour to be influenced by the fact that a certain aspect is given attention, first attributed after 1920s studies on worker productivity under varying lighting conditions conducted in the Western Electric Hawthorne Plant located in Illinois[18].

In this case, the building owners or managers had to be notified that the door position logging devices were being placed in their buildings. This could have influenced their behaviour in different ways: they may have been made more aware of the need to keep fire doors closed by the fact that the study was being conducted and thus adjusted their behaviour based on this change in knowledge, the presence of the devices may have been a reminder to the building occupants to close the door if they happened to observe a device when passing through a door, or they may have wanted to demonstrate that their building was meeting fire safety objectives by adjusting their behaviour and keeping the doors closed.

This effect could also be present for “snap-shot” inspection type data collection if any of the building occupants received information that an inspection was taking place prior to the inspection. A way to avoid this issue for future data collection would be to embed the devices in fire doors so they are not visible when they are installed and monitor the position over the lifetime of the doors. It is unknown if there would be any legal implications of tracking door position without notifying the building personnel. It might have to be written into the building regulations or compliance schedule requirements to be successfully implemented.

9.12 Conclusions

A new method of collecting data on passive building elements has been developed which leverages inexpensive modern microcontroller and sensor technology. Use of the new method has been demonstrated for short term building evacuation and long term reliability data collection. The evacuation data showed that door negotiation times for single occupants ranged from 3 to 7 s. For multiple occupants using a door, the negotiation times were found to be between the values calculated using the C/VM2 queuing time method and 3 s per occupant.

Long term door reliability data for hinged doors with self-closers but no magnetic hold open devices was reported for 52 doors in four types of buildings including rest homes, hotels/backpackers, apartments/condos, and boarding houses/dorms. Door reliability was found to be skewed, with the majority of doors closed most of the time and a few doors open for long periods of time. The average door reliability was found to be higher than observed in a 1970 UK study, discussed in Chapter 8.

Rest home doors were found to be closed most often followed sequentially by hotel/backpackers, apartment/condo, and boarding house/dorm doors. Other than for hotel/backpacker building types, there was negligible difference between working hours and non-working hours and between weekends and weekdays.

It is not possible to determine if the building occupants' behaviour was influenced by the study itself. Future data collection would have to be undertaken without the knowledge of the building occupants to eliminate this source of uncertainty in the validity of the data.

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CHAPTER 10

SMOKE MANAGEMENT SYSTEM EFFECTIVENESS

10.1 Introduction

Smoke spread in buildings during a fire is a major hazard to life safety. Fatalities can occur in areas of the building far removed from the actual fire, as observed in the November 21, 1980 MGM Grand fire[1] in Las Vegas, Nevada, USA and October 17, 2003 Cook County Administration Building fire[2] in Chicago, Illinois, USA. In the MGM Grand fire, direct fire damage was reported to be limited to the first 2 floors, yet 61 of the 85 fatalities occurred on floors 16 and above. In the Cook County fire, six people died in a locked stairwell well above the fire on the 12th floor of the 36 storey building. Smoke management systems take one or both of two approaches: remove smoke from a space or prevent smoke from entering a space. Smoke extract systems are an example of the first type; stairwell (safe path) pressurisation systems are an example of the second. Zone smoke control systems can combine both approaches; pressurising uncontaminated areas and extracting smoke from contaminated areas.

It was noted by the assessment reviewer in the first SME determination (discussed later in Chapter 11) that *"the pressurisation system is the key component in this building in achieving fire safety"*, even though the fire risk in that building was shown to be more sensitive to the sprinkler system effectiveness.

The systems discussed in this chapter consist of mechanical ventilation, either pressurising or extracting smoke from a space, and either activated by a smoke detector or manually activated. Uncertainty in system reliability and B-RISK's tools to model the operation of smoke management systems are discussed. While a smoke control system could be activated by any type of smoke or heat detector, discussions in this chapter will be limited to smoke detectors. For activation by a heat detector, the methods discussed in Chapter 5 are applicable with appropriate inputs.

10.2 Smoke management system effectiveness data

Relative to sprinkler systems, little data is available on the effectiveness of smoke management systems. PD7974-7:2003 states that there is little data on smoke control system effectiveness available, but the data that is available suggests reliability of 85% to 90%[3]. Smoke management systems are not as common as sprinkler systems. Most fire incident data collection systems, such as the US NFIRS system or the NZFS Station Management System do not provide explicit data fields for including the performance of these systems in fire reports. Unlike activated sprinklers, much of the operational equipment of a smoke management system such as fans and dampers are not intimate with the location of the fire products. It is more difficult to evaluate if a smoke management system has met its objectives as well, particularly for extraction systems, since the quantities of produced smoke and removed smoke are difficult to estimate.

It may be easier to estimate system performance for pressurisation systems by monitoring the air pressure in the relevant compartments (the fire compartment and the pressurised compartment). Products exist for monitoring and logging compartment pressures in critical applications, such as healthcare isolation facilities[4] and cleanrooms. However, no data on the ability of pressurisation systems to maintain their target pressures in fire situations has been identified. While this measure would not directly evaluate the ability of the system to keep smoke out of the protected area, it would provide information on the ability of pressurisation systems to meet their differential pressure targets.

Klote and Milke[5] considered the effects of system complexity on the reliability of smoke control systems before commissioning and the mean life of a system after commissioning. A number of assumptions were made which limit the application of Klote and Milke's analysis to real systems. Systems were assumed to be series systems where operation of all components were required for operation; the entire system was assumed to fail completely if one component failed and there was no consideration of partially effective operation. All components were assumed to be operational after commissioning. The reliability of shared components with other building systems (eg. HVAC fans) was assumed to be higher than smoke management specific components due to ongoing occupant requirements, particularly components required for occupant comfort in extreme weather. An arbitrary reliability of 0.99 was used for shared components since it was expected to be near unity. A reliability of 0.94 for smoke management system specific components was used based on field experience with such systems. System reliability before commissioning was estimated to range from 0.97 with a mean commissioned life of 116 months for a system sharing only three HVAC system fans to 0.03 pre-commissioning reliability and three month mean commissioned life for a system with five shared HVAC fans and 54 smoke management system-specific components.

Fazio[6] discussed the effectiveness of stairwell pressurisation systems. She noted that pressurisation effectiveness was sensitive to the commissioning process which could take years. It was also noted that leakage could develop over time.

Zhao[7] discussed the reliability of zone smoke control systems and stair pressurisation systems using fault tree analysis. System components considered in this analysis were the power supply, fire indicating panel (FIP), detectors, connections, fans, and dampers. Power supply failure was considered negligible due to daily use and likely presence of backups. The failure rate of the panel was estimated to be 0.00306 using data from Lees[8]. Detector and connection failure rate was assumed to be 0.000432. Fans were assumed to be used for normal daily operation and thus faults were assumed to be promptly fixed, with a one day repair time. A sensitivity analysis for the effects of maintenance uncertainty on fan reliability was conducted, resulting in a range of fan reliability from 0.981 to 0.999, although a single value of 0.995 was used for the remainder of the analysis. The probability of a damper failing to open was estimated to be 0.0857, and the probability for a damper to fail to close was estimated to be 0.0002. The potential for other vents such as doors and windows to be open and affect the performance of the system was not discussed. Zhao estimated the reliability of a single fan stairwell pressurisation system to be 0.90 using the values reported above.

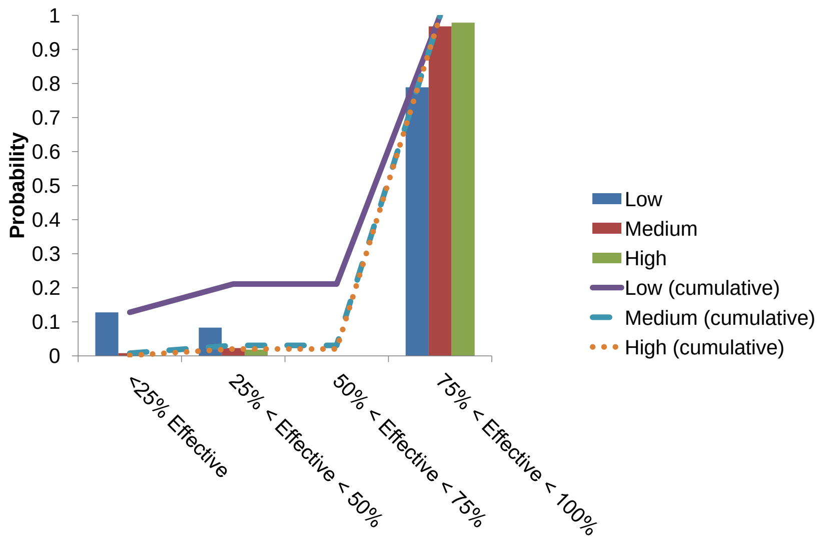
For estimating the reliability of a zone smoke control system, Zhao took an approach of separating the performance of the system into four categories: complete failure, partial failure, likely reliable, and completely reliable. The required components to maintain a pressure difference on the fire floor were used as the criteria for placing the performance of the system in one of these categories. In order to provide the minimal pressure difference, the supply air damper on the fire floor and the recycle air damper for the building were required to be closed, and the return air damper on the fire floor and the exhaust air damper for the building were required to be open. Partial performance was determined by the number of return air dampers on other floors that failed to close. Failure of supply air dampers on non-fire floors was neglected as these were assumed to be open for normal operation.

Moore and Timms[9] looked at smoke control systems in Australian shopping malls and department stores. These systems split up the building space into smoke reservoirs or zones with smoke barriers and used exhaust fans in each zone to remove smoke. Fans in adjacent zones were used to supply make-up air. Two types of systems were considered; one which used the return air ducting to remove the smoke and one which had separate exhaust ducting. The zones were limited to less than 60 m in length and fans were required to be spaced no more than 40 m apart by the Building Code of Australia (BCA). The systems were required to be activated by smoke detectors.

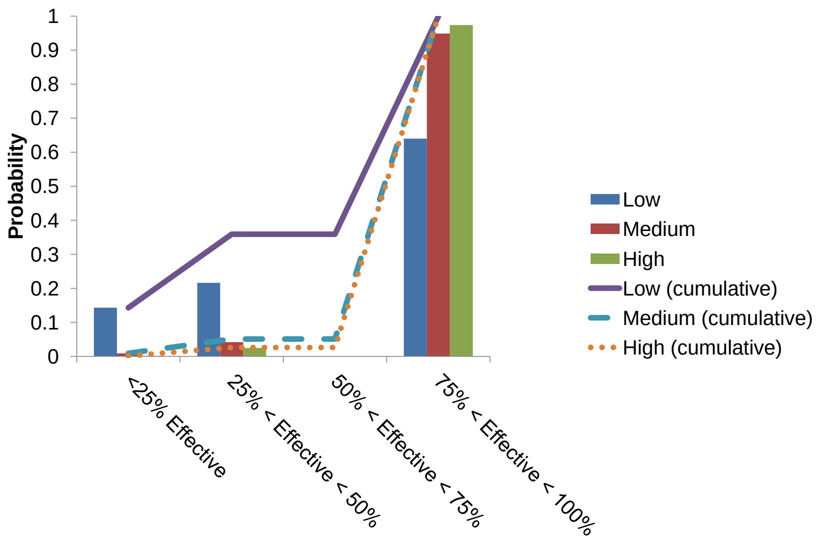
Moore and Timms conducted fault tree analysis on the major components of the systems, including the detection system, power supply, exhaust and supply air fans, and return and outside air dampers. The effects of low, medium, and high quality for maintenance, installation and commissioning were included. The effects of different components failing on the system efficacy were evaluated by considering 10 scenarios of efficacy ranging from 0% (for example, if no signal was received from the detection system) to 100% (if all components operated as designed). Probability distributions for the estimated effectiveness for the two systems can be seen in Figure 10.1.

Yashiro et al[10] provided an estimate of 0.974 on the reliability of a smoke extraction system based on annual inspection data from 1989 to 1997.

Gravestock[11] provided a literature review on smoke management system component data. Using fault tree analysis, he estimated smoke detection reliability to range from 0.9 to 0.99 with an expected value of 0.981 for a simple system and from 0.72 to 0.99 with an expected value of 0.88 for a complex system.



(a) System 1



(b) System 2

Figure 10.1: Distributions of smoke control system effectiveness from Moore and Timms[9].

	Const. aspects incl.			Const. aspects not incl.		
System type	**Lower**	**Expected**	**Upper**	**Lower**	**Expected**	**Upper**
Fixed speed fan and barometric dampers	0.11	0.36	0.77	0.28	0.6	0.84
Variable speed drive system	0.06	0.28	0.73	0.14	0.47	0.8
Variable speed drive and motorised damper system	0.07	0.31	0.74	0.16	0.52	0.82

Table 10.1: Gravestock's[11] estimated stairwell pressurisation reliabilities for three system configurations. Construction aspects included door hardware and building assembly leakage.

Gravestock also used fault trees to estimate stairwell pressurisation system reliability, shown in Table 10.1. Gravestock's fault trees include detection system, damper, fan, construction aspect, and control panel failures. The construction aspect included door hardware failure and building element leakage.

None of the studies identified include smoke management system performance in real fires, but are either based on inspection data, component data, or expert judgement. The lack of available data on smoke management systems results in large uncertainty.

10.3 Detection uncertainty

10.3.1 B-RISK smoke detector response model

B-RISK can estimate the activation of a smoke detector using two methods: by approximating the detector as a heat detector or by estimating optical density, methods that are also described in the IFEG[12]. The heat detector approach uses the same detection model as discussed in Chapter 5 with empirically determined input parameters for activation temperature and RTI that give approximate smoke detector activation times. In the context of fire modelling, optical density[13] is a measure of the amount of light absorbed by the fire products in the air. The optical density OD is predicted from the soot concentration using the specific extinction coefficient k_m:

$$OD = \frac{C_{soot,cj} k_m}{2.3} \tag{10.1}$$

The specific extinction coefficient used by B-RISK was measured for ethene smoke[14]. The soot concentration at a smoke detector that is located in the ceiling jet $C_{soot,cj}$ is estimated using the method developed by Davis[15]. For detectors that have the sensor positioned in a housing, B-RISK uses Heskestad's method for estimating the response of smoke detectors based on the optical density (or visual obscuration) inside the detector cavity[16]. Detector response time is calculated using the following procedure:

$$\frac{\partial D_i}{\partial t} = \frac{1}{\tau} (D_o - D_i) \tag{10.2}$$

where D_o and D_i are the smoke optical densities outside and inside the detector, respectively, and τ is a detector time constant. The time constant is calculated as follows:

$$\tau = \frac{l}{u} \tag{10.3}$$

where l is a characteristic length based on the detector geometry and u is the ceiling jet velocity, calculated using the same approach described in Chapter 5. It has been noted that this approach does not give good results at low ceiling velocities[17]. Detector actuation is estimated using sensitivity limits given in AS 1603.2, which are described as applicable to photoelectric smoke detectors and conservative for ionisation detectors in flaming fires[16], which are two of the most common types of smoke detectors in use, along with linear beam detectors and aspirating detectors[18].

10.3.2 Uncertainty in soot production

The estimated soot concentration is dependent on the modelled soot generation. The mass of soot generated by the fire $\dot{m}_s$ is calculated from the mass of materials combusted in the fire $\dot{m}_f$ by a soot yield ψ_s

$$\dot{m}_s = \psi_s \dot{m}_f \tag{10.4}$$

The mass loss of the combusted materials is calculated from the estimated heat release rate Q by dividing by the heat of combustion ΔH_c

$$\dot{m}_f = \frac{Q}{\Delta H_c} \tag{10.5}$$

Distributions for the heat of combustion and soot yield can be entered into B-RISK. Distributions for these parameters from previous fire test data are available in the literature[19].

10.3.3 Uncertainty in gas velocity

Ideally, smoke detectors will detect a fire as early as possible when it is small. At this stage of a fire the ceiling jet is not well established and existing currents in the room from ventilation equipment can dominate the gas movement at a smoke detector. Geiman and Gottuk[20] found that smoke detector response could be influenced significantly by ventilation.

If the potential for ventilation to influence smoke detector response exists in a scenario, the characteristic length distribution can be adjusted to include these effects.

10.3.4 Uncertainty in detector activation physics

The four commonly used detector types all use different methods of detecting smoke. Of the four, only the linear beam type directly measures light obscuration or optical density OD[21]. Beer first postulated that optical density per unit length l is proportional to the molar concentration of the light absorbing species:

$$\frac{OD}{l} \propto C_{soot} \tag{10.6}$$

For soot, Fabian and Gandhi found that the molar concentration was proportional to the sum of the product of the number of particles and the particle diameter cubed, or[22]:

$$C_{soot} \propto \sum n_i d_i^3 \tag{10.7}$$

Thus,

$$OD \propto \sum n_i d_i^3 \tag{10.8}$$

Photoelectric smoke detectors measure light scattering s due to the Tyndall effect and have been shown to have a response proportional to the sum of the product of the number of particles and the particle diameter squared, or[22]:

$$s \propto \sum n_i d_i^2 \tag{10.9}$$

and which also depends on the colour of the particles[21,22]. Aspirating smoke detectors are a specialised form of photoelectric detector which use a controlled method of sampling the environmental gases through tubing and a controlled laser pulse which increases sensitivity by orders of magnitude relative to conventional photoelectric detectors[18].

Ionisation detectors measure the rate of ions traversing from a radiation source to a sensor (ΔMIC)[18]. The output of ionisation detectors has been shown to be proportional to the sum of the product of the number of particles and the particle diameter, or[22,23]:

$$\Delta MIC \propto \sum n_i d_i \tag{10.10}$$

Commercial detectors may also use multiple smoke detecting methods and integrate the signals using proprietary algorithms to reduce false alarms, which also increases uncertainty in estimating the detection time. Quantifying this uncertainty is difficult due to the proprietary nature of the detector design, and would require

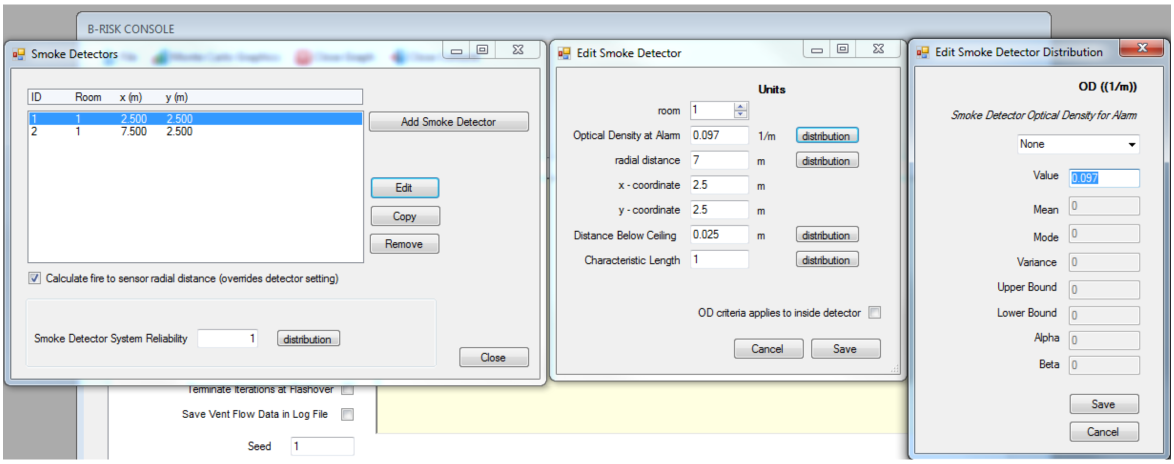


Figure 10.2: B-RISK forms for entering smoke detectors. Multiple smoke detectors can be entered in the fire room, with distributions for optical density at alarm, radial distance, distance below ceiling, characteristic length, and reliability (one reliability for the entire smoke detection system).

testing of specific detector models in the range of conditions expected for a specific building design.

Most fire and smoke spread models including B-RISK do not have the capability to estimate the number and diameter of smoke particles. Soot lost from the air through deposition on surfaces is not accounted for in B-RISK. In deterministic models, the optical density or temperature rise approaches discussed previously are used with conservative threshold values[24]. However, B-RISK allows for a distribution to be used for the optical density at alarm for smoke detectors, as shown in Figure 10.2.

Data from previous tests where optical density at alarm was measured can be used to estimate the distribution of optical density or temperature rise required for alarm. Several sets of test data are available, including tests conducted by the US Navy[25] and the Canadian National Research Council[26]. In this work the Navy test data was used to develop distributions for optical density at smoke detector response, shown in Figures 10.3 to 10.6. Summary statistics including Kolmogorov-Smirnov statistics for best fit log normal distributions for the US Navy data are shown in Table 10.2.

There was much more uncertainty in the optical density at alarm for smouldering fires for both types of detectors, with standard deviations an order of magnitude larger than for flaming fires. Ionisation detectors were slightly faster on average for

Detector type	Fire type	Mean ln(OD/m at alarm)	Standard deviation ln(OD/m at alarm)	K-S statistic
Ionisation	Flaming	-4.65	1.01	0.0803
Ionisation	Smouldering	-2.98	1.15	0.0660
Photoelectric	Flaming	-3.55	0.55	0.0828
Photoelectric	Smouldering	-3.32	1.24	0.0741

Table 10.2: Summary statistics for US Navy smoke detector test data, including Kolmogorov-Smirnov test for best fit log normal distributions.

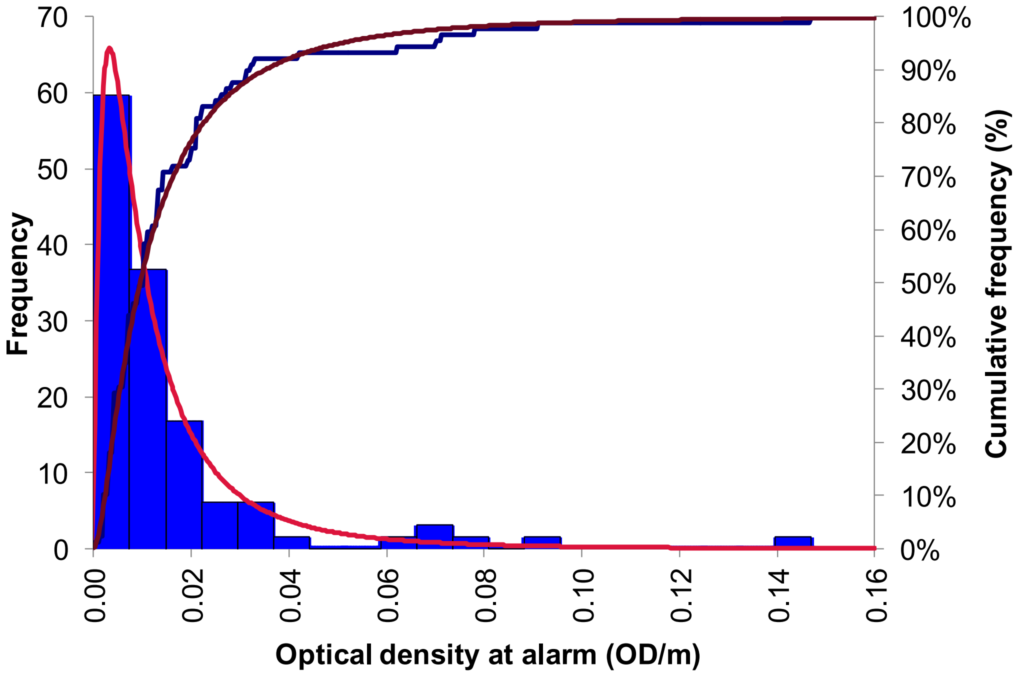


Figure 10.3: Distribution of optical density at alarm measured in US Navy tests for ionisation detectors with flaming fires.

flaming fires and photoelectric detectors were slightly faster on average for smouldering fires.

10.4 Uncertainty in modelling smoke movement

The objective of a smoke management system is to either keep a space free of smoke or to remove smoke. Therefore, to model the effect of a smoke management system, the amount of smoke produced by the fire and its movement is required.

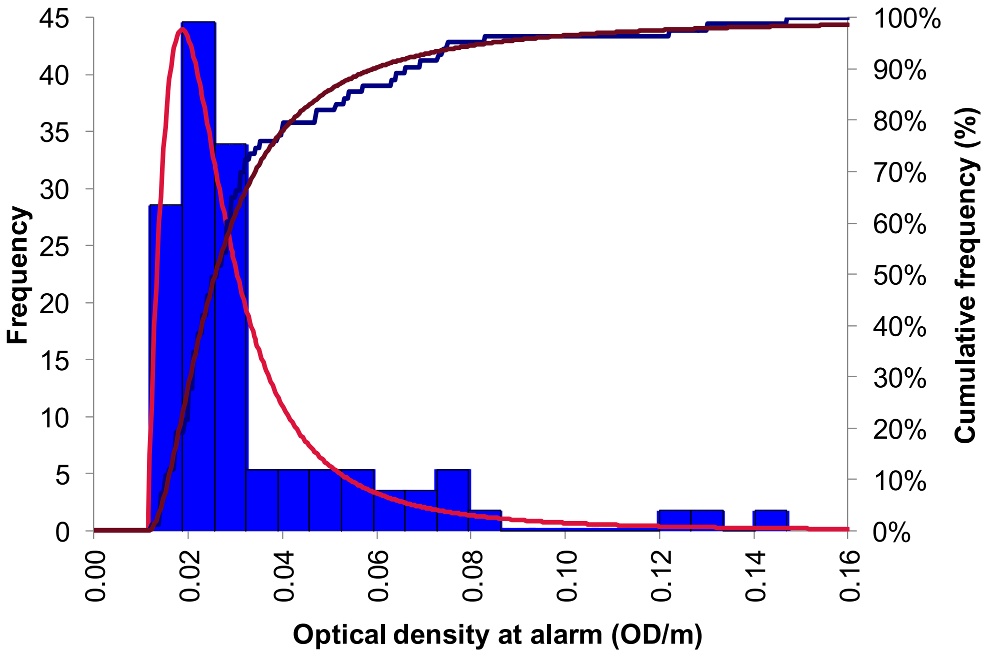


Figure 10.4: Distribution of optical density at alarm measured in US Navy tests for photoelectric detectors with flaming fires.

As discussed in Section 10.3.2, B-RISK uses the estimated heat release rate, heat of combustion, and species yields to calculate fire product generation rates. The volume of smoke produced with the fire products also depends on how much air is entrained with the products in the fire plume. B-RISK allows several plume entrainment submodels to be used. The zone model assumptions of homogeneous zones and negligible gas momentum outside of the plume and vent flows add uncertainty.

10.4.1 Uncertainty in modelling smoke filling

Smoke extraction systems are typically designed to keep the smoke layer above the heads of egressing occupants. Thus, the ability of the model to estimate layer height is critical. However, it is difficult to evaluate the layer height in experiments because there is often no clear horizontal interface, which introduces a source of uncertainty in verification data. In some cases, a clear interface may be visible but the exact height is dependant on the observer. Less subjective methods such as the N percent

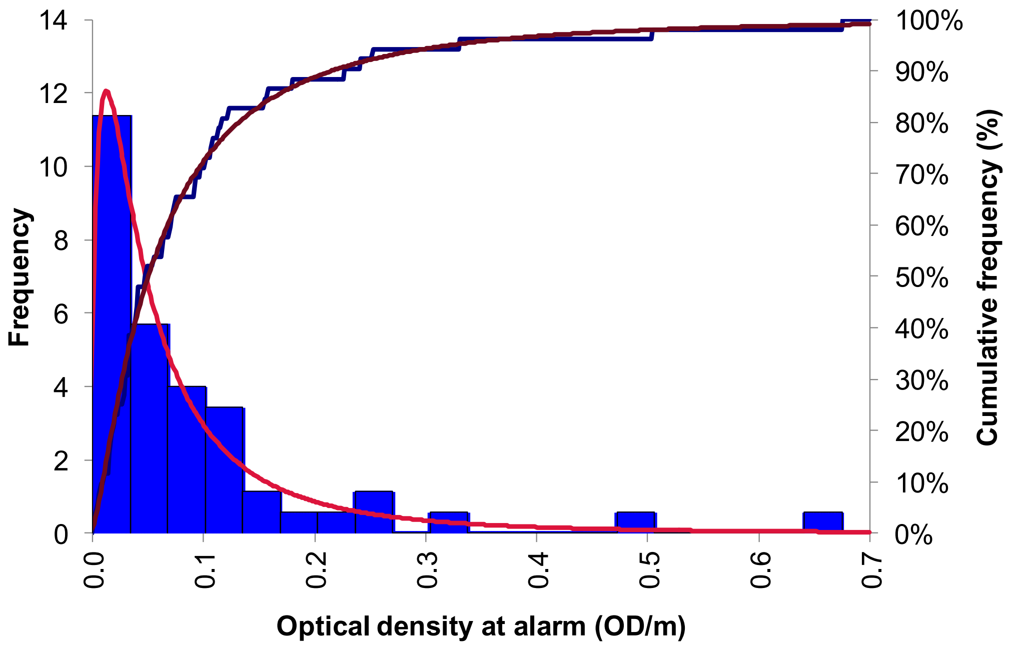


Figure 10.5: Distribution of optical density at alarm measured in US Navy tests for ionisation detectors with smouldering fires.

approach[27] may be used to evaluate the smoke layer height experimentally, particularly in instances where an interface is not clearly visible. However, these methods also include uncertainty. Uncertainty in the ability of zone models to predict layer height is a function of the scenario geometry and fire conditions, because the relative effects of the model assumptions and inputs will change for different scenarios. An example is smoke transport time, which is neglected in many zone models including B-RISK, which will create larger uncertainty with the larger transport distances associated with larger compartment geometries.

Plume entrainment models assume quiescent conditions and do not account for the potential for additional air to be entrained in the plume from air movement from other sources such as wind or mechanical ventilation. B-RISK includes a "disturbed plume" option that doubles the entrainment where such conditions exist, however actual effects in real fires will vary. Externally forced air movement is a source of uncertainty for modelling smoke filling that is not generally present in experimental verification data used to verify plume entrainment models. The uncertainty from these effects may be more realistically dealt with in a field model

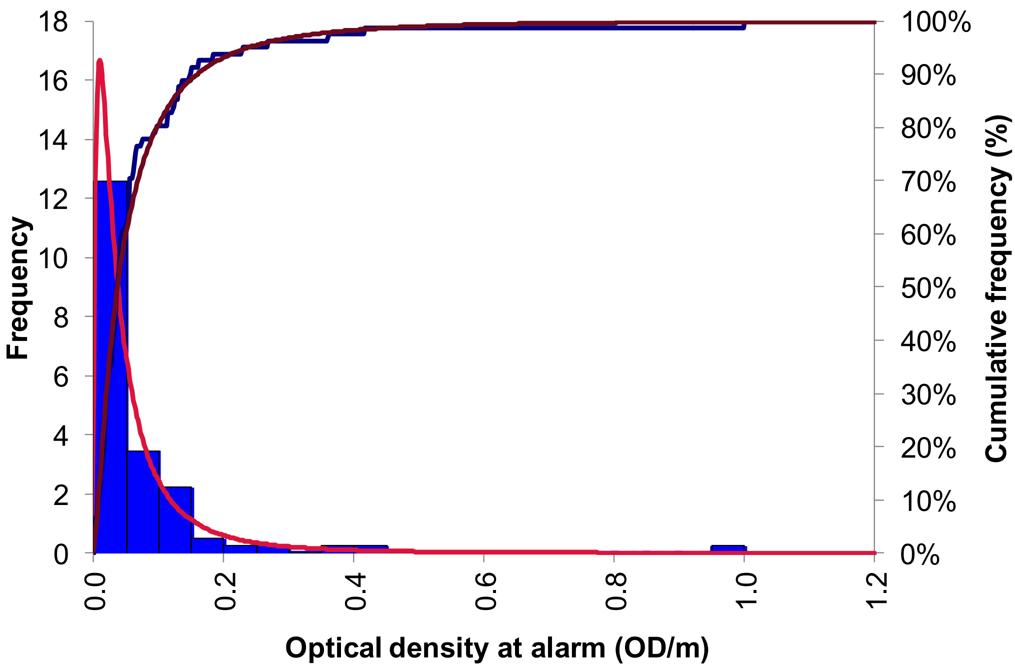


Figure 10.6: Distribution of optical density at alarm measured in US Navy tests for photoelectric detectors with smouldering fires.

that includes momentum effects throughout the gas phase simulation, if appropriate probabilistic external drivers are added.

Chapter 5 discussed the uncertainty in BRANZFIRE for the layer height in the Steckler experiments. For the Steckler experiment geometry, which involved steady fires from 32 kW to 158 kW in a 2.8 m square by 2.13 m high room with a single horizontal vent opening, the model was found to overpredict the layer interface height by a mean of 11% with a standard deviation of 28%.

Vigne et al[28] compared various zone models and correlations including BRANZFIRE with experimental smoke layer heights for a nominally 1.5 MW heptane pool fire in a 20 m x 20 m x 20 m atrium with mechanical ventilation. The N% method was used to determine the layer height experimentally, using 30% of the maximum temperature rise as the cut off. The uncertainty in model correlations was estimated to be nominally 35% with a maximum of 100% for one correlation.

10.4.2 Modelling smoke movement in vertical shafts

In B-RISK, there is an option to use a single zone for a compartment which assumes that the smoke is well-mixed throughout the volume of the compartment. This approach has been recommended for shafts with a height to width aspect ratio greater than two due to reduced entrainment as the plume contacts the walls[29]. This option is another source of decision uncertainty in B-RISK.

Work has been done by Wade[30,31] to benchmark the performance of B-RISK, including comparison to FDS results for modelling smoke movement in vertical shafts. It was found that modelling a shaft with a height to width aspect ratio greater than five as a single zone provided a conservative estimate of the smoke concentration away from the plume source from B-RISK, compared to FDS. However, B-RISK tended to under predict the smoke concentration near the plume source. An improved outcome was obtained in B-RISK by modelling the shaft as two separate single zone compartments, one encompassing the shaft volume near the plume source and the other including the remainder of the shaft volume.

10.5 Mechanical vents

B-RISK includes the ability to model mechanical ventilation using either a fan curve or a set pressure/flow. The input windows for mechanical ventilation are shown in Figure 10.7.

10.5.1 Pressurisation uncertainty

Klote and Milke[5] noted that there may be a large amount of uncertainty in the pressure difference produced by a smoke control system, although it was difficult to quantify the amount of uncertainty due to the large number of factors involved, including wind, leakage paths, building geometry, and smoke characteristics. Up to 50% deviation was suggested as tolerable for most conditions.

To account for the potential for deviation in pressure difference, a distribution may be applied to the fan curve pressure differential in BRISK. It is doubtful that detailed information on the pressure differential fluctuation will be available, so a $\pm 50\%$ uniform distribution based on Klote and Milke's information may be used to test the fire risk sensitivity to the potential for pressure differential fluctuation.

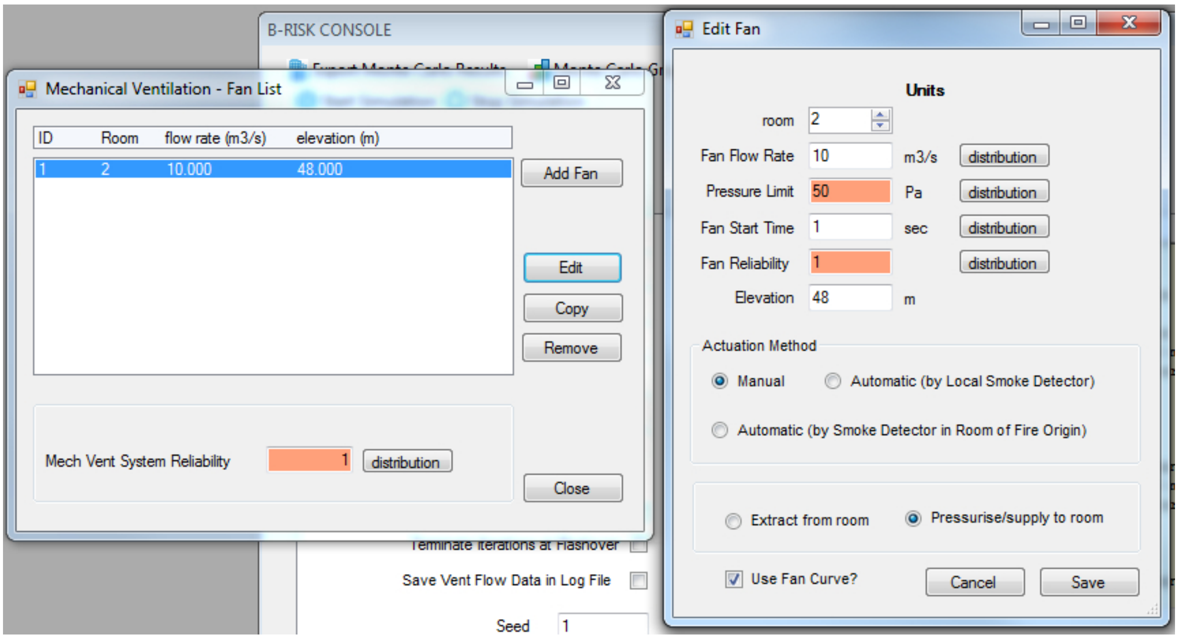


Figure 10.7: B-RISK forms for entering mechanical ventilation (fans). A system reliability distribution is available as well as individual reliability distributions for each fan. Distributions can be entered for the fan flow rate, pressure limit, and start time as well.

10.5.2 Mechanical smoke extract uncertainty

Uncertainty in the extraction flow rate when fans are used will depend on the fan characteristics, building geometry, and weather conditions. Each design situation should be evaluated on an individual basis.

10.6 Effects of sprinkler activation on smoke management systems

As mentioned in Chapter 7, sprinkler activation affects the properties of smoke produced by the fire. The change in smoke properties will produce additional uncertainty in the ability of the smoke management system control smoke movement. B-RISK does not currently include any capabilities to account for these effects.

10.7 Conclusions

There is much less information available to evaluate the effectiveness of smoke management systems in risk-informed fire safety design compared to suppression systems. This is due to a number of factors including the difficulty in determining if a smoke management system has met its objectives in a real fire, the smaller population of smoke management systems, the greater variety of designs, and interaction with other systems.

An interesting piece of future work would be to determine if pressurisation system pressure sensor data is available from any systems operating in real fires, or to endeavour to make this information available for future collection in new or retrofitted pressurisation systems. While this data would not specifically address the performance of the pressurisation system in preventing smoke movement into designated areas, it would allow objective analysis of the efficacy of pressurisation systems in meeting their design pressure specifications in real fire events.

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CHAPTER 11

FIRE RISK CASE STUDIES

This chapter describes four fire safety case studies relevant to this research. Two case studies describe risk-informed fire safety in New Zealand sleeping occupancy buildings where fire safety system effectiveness was a critical factor in the risk outcome. A third example discusses a risk-informed fire safety analysis that was conducted for the refitting of a commercial building in Australia. The fourth case study discusses a fire in a seniors' complex in Alberta, Canada, where fire safety system effectiveness was a major factor in the spread of the fire and resulted in changes to the building regulations.

11.1 New Zealand and Australian probabilistic fire safety design case studies

There are precedents for the use of risk-informed fire safety building design in New Zealand and Australia. The following sections describe three case studies where a risk-informed basis has been used.

11.1.1 Report on the impact on life safety of the Type 5 alarm

In the report written for the NZFS entitled "Impact on Life Safety of the Type 5 Alarm", Enright[1] looked at the increase in risk with the introduction of the Type 5 alarm in the June 2001 revision of C/AS1. A Type 5 alarm allows *"part of the smoke detection component to comprise only a local alarm"*[2], alerting only the firecell

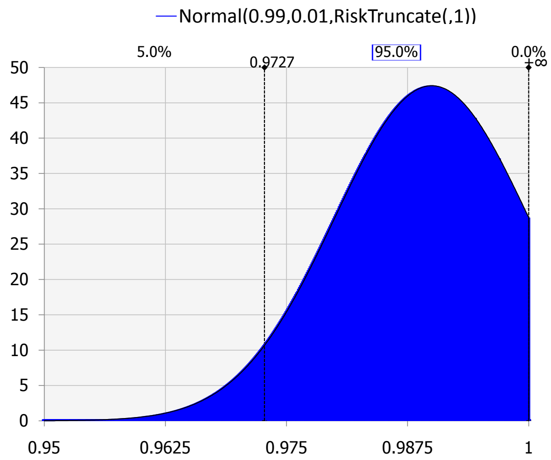

Figure 11.1: Sprinkler reliability distribution from Type 5 alarm report[1].

occupants and building management if available. The Type 5 is an alternative for Type 4 or Type 7 alarms. A Type 4 alarm is *"A detection and fire alarm system which activates automatically in the presence of smoke, and can be activated manually at any time."* A Type 7 alarm combines a sprinkler system with smoke detectors and manual call points.

Enright based his sprinkler system reliability distribution on Marryatt's[3] study stating that *"Marryatt reports sprinkler reliability at 99.5%... the high value is assumed suitable rounded down to 99% as NZ has an effective regime of installing, commissioning, and maintaining systems."* Enright assumed the standard deviation would be equal to the difference between the mean of .99% and 1.00 and used a normal distribution. The distribution was truncated at 1.00, since the probability that the system operated cannot exceed 1.00. The sprinkler reliability distribution used can be seen in Figure 11.1.

The automatic alarm reliability information was obtained from British Standard's Institute DD240, which was superceded by PD7974. In the Type 5 alarm report, the reliability is used for the event of "unawake occupants receiving an automatic smoke alarm," and a mean value of 90% is used. However, PD7974-7:2003 states that *"smoke and rate of rise heat detectors are generally expected to detect a fire in approximately 90% of cases."*[4] It then indicates that the reliability *"might be reduced to approximately 75% or lower in the case of domestic smoke detectors."* This only considers the activation of the detector, it does not consider the reliability of the connection be-

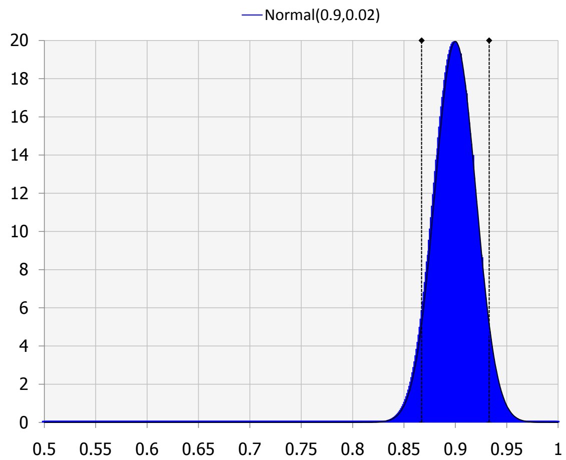

Figure 11.2: Alarm reliability distribution from Type 5 alarm report[1].

tween the detector and alarm mechanism and does not consider the reliability of the occupant to respond to the alarm. Enright assigned a standard distribution of 0.02 to the automatic alarm reliability, and used a normal distribution, but his rationale for these choices is not stated in the report.

Enright provides the distributions for total acceptable loss of life (TALL) for 4 scenarios, including both of the Type 4 and 7 alarms and the effect of the Type 5 modification each. He compares the effect on the mean TALL for switching to the Type 5 alarm (his conclusion was that it increased the risk to life by approximately 20% in both Type 4 and 7 systems) and also the effect of the sprinklers (which reduced the risk by approximately two orders of magnitude with and without Type 5 modifications). He also discussed the sensitivity of the TALL output to the input parameters, and found that the Type 7 scenarios were most affected by uncertainty in the sprinkler reliability, more so than whether the occupants were awake or not. None of the scenarios were particularly sensitive to the alarm reliability, which was consistently ranked in the middle of the input parameters in terms of sensitivity, generally less than the probability of fire ignition, location (sleeping area or not), and if the fire was confined to the room or the floor of origin.

In his conclusions, Enright noted that *"The use of Monte Carlo methods does not eliminate the need to define and justify the relevant probability distribution functions and does not provide a rationale for the default usage of any simple standard distributions (e.g. uniform, normal)"*[1]

11.1.2 Single means of escape determinations

In 2005 and 2006, the fire safety designs for 6 apartment buildings in Auckland were brought to the DBH determination process. While each building was unique, the proposed designs for these buildings all had two fire safety features in common: only one means of escape, and an escape height greater than 25 m. The acceptable solution C/AS1 required the following features for multi-unit residential buildings with an escape height exceeding 25 m [2]:

- Automatic fire sprinkler system with smoke detectors and manual call points;
- **Two separate means of escape separated by fire rated construction;**
- Firecell rating to be no less than F30;
- Fire separations of the safe path to be 30/30/30 (reduced from 60/60/60 due to provision of sprinklers);
- Lifts to be within a protected shaft;
- Exit doors from apartments are required to open directly onto a horizontal safe path, a pressurized vertical safe path, or a final exit; and
- A horizontal protected path at each floor level other than the top floor shall precede the vertical safe path. The protected horizontal path and vertical safe path shall be separated by fire doors.

Additional features were required with escape heights above 46 m (a Fire System Centre where the NZFS can monitor and control fire safety features) and above 58 m (a pressurisation system). An additional means of escape took up building space which was valuable especially in high population density areas where building footprint area was at a premium. Also, if an existing building was modified such that the escape height increased beyond 25 m, the original single means of escape no longer met the acceptable solution criteria. Eliminating one means of escape required an alternative solution to meet the building regulation requirements. Each building, being unique, had different features proposed to compensate for the single means of escape.

The analysis for each of the determinations was based on a comparative probabilistic event tree analysis where the alternative solution building with the single means of escape was compared to a building design that was compliant with C/AS1 but with similar layout and occupancy characteristics. The alternative solution had to have a three to one "risk margin" or 75% probability of being safer than the compliant design. The rational for the risk margin being increased from one to one (which it would be for a comparison between identical compliant buildings) was given in the Determination 2005/109 summary document, written by the DBH Determinations Manager:[5]

- *6.2.4 In this case, I consider that the type of comparative risk analysis used in the assessment is an appropriate method for deciding whether an alternative solution is effectively equivalent to the corresponding acceptable solution in terms of fire safety. In particular, I accept the following comment from Expert D: In considering changes to the fire safety system in a building of the sort proposed (deletion of a stairway, improvements to the sprinkler system, stair pressurization, etc) it needs to be understood that each of these changes affects the level of fire safety in the building in different ways. Consequently the only way of comparing these changes is on a risk basis how much (and in which direction) each of them changes the level of safety in the building.*
- *6.2.5 However, I recognise that there is as yet inadequate data for fire engineering to achieve the accuracy that is expected from, for example, structural engineering. In particular, the probabilities used for a fire analysis must be based on fire statistics derived from a comparatively small data pool of mainly overseas buildings of unknown design. That applies not only to fire scenarios but also to the proper functioning of critical systems including the sprinklers, the pressurisation system, the smoke detectors and fire alarms, the automatic drop windows, and the door closers. There appears to be no certainty as to the extent to which those statistics and probabilities are appropriate for use in the New Zealand context.*
- *6.2.6 That does not mean that the method cannot be used in New Zealand, but it does mean, in my view, that the results of such analyses need to establish a high probability that an alternative solution building would be safer than the corresponding acceptable solution building in all relevant fire scenarios and across a realistic range of probabilities.*
- *6.2.7 In this case, I do not consider that the 51 to 74% probability mentioned in 5.3.6 above is high enough.*

These statements in Determination 2005/109 set the precedent in New Zealand that quantitative probabilistic comparative risk assessment was an acceptable method to evaluate trade-offs for a single means of escape in a high-rise residential building, which was then used for at least five subsequent cases which have been documented by determinations. In addition, residential buildings with similar SME configurations have been reportedly granted consent in New Zealand since the determinations but have not been subjected to the determination process. The following sections discuss the features of each building that went through the determination process. A summary of the building features and fire safety features intended to compensate for the single means of escape is given in Table 11.1.

11.1.2.1 Determination 2005/109

The first building had 18 storeys, with an entrance lobby, service space, and a loading bay on level one, three apartments, an office, and a plant room on level two, and six apartments of approximate floor area 27 m^3 on levels three through 18. All of the apartments were either bed sitting rooms or single-bedroom dwellings. The building had a maximum escape height of 48 m from the top floor. The apartments, stairway, and the service areas on levels one and two were sprinklered. The atrium and stairway were pressurized by three fans in the roof and one at ground level. Consent for this building had been issued on February 10, 2004 by the TA, and the NZFS applied for determination on June 9, 2004. The building was nearly completed at this point. At the time that the determination process had been concluded, the building was complete but no code compliance certificate had been issued.

The fire safety issue driving the determination was the safety of building occupants outside the compartment of fire origin. As the apartments opened directly onto the stairwell, there was a concern that if the door to the apartment of fire origin was left open that occupants on the levels above the fire would be at risk. An example of a real fire where a similar circumstance occurred was the 2 Forest Laneway fire in North York, Ontario, Canada, on January 6, 1995[6].

Determination/Address	Above Grade Levels	Tower Description	Total Number of Apts.	Max. Escape Height (m)	Difference from C/AS1
2005/109 - Single tower 5 Princess Street	18	Level 1 contains entrance lobby, service space, and loading bay. Level 2 contains 3 apartments + office. Levels 3 - 18 have 6 apartments each	51	48	Single escape route, sprinkler system enhanced with dual street main supply, FR heads, Type 2 FS connection, 60/60/60 FRR rather than 30/30/30, staged evac scheme w/ Type 8 voice communication system
2005/134 - Single tower 2-30 Beach Road	16	Basement + 3 level podium with carparking and retail + 12 level apartment tower. Mirror image with solid concrete wall in centre, non-intercommunicating	106	43.6	Single escape route, dual pump for spinkler system, safe path pressurisation (stairway only), staged evac scheme w/ Type 8 voice communication system
2005/168 - Single tower 7 Scotia Place	15	Level 1 contains service rooms and 7 apartments, level 2 has an entrance lobby, office space, caf, and 12 apartments, level 3 has 15 apartments, levels 4 - 15 have 16 apartments each	226	37.8	Single escape route, dual ”Class A” water supply w/ tank, safe path pressurisation(stairway only), Type 8 voice communication system
2005/169 - Two towers above 4 levels of basement carparking, connected on all adjacent levels 10-14 Upper Queen Street	12 4	6 apartments per level Level 1 includes entrance and reception, offices and services, plus 2 apartments, levels 2-4 have 6 apartments	72 20	31.9 8.4	Single escape route, dual ”Class B”water supply with a tank, safe path pressurisation (stairway only), voice communication system
2006/34 - Single tower 47 Wakefield Street	10	Original 8 storey building converted to 10 storey	6 new 2 level apts. on lvls. 9-10	29.3	Single escape route, smoke alarm systemsto NZS4514:2002 (less than required in C/AS1), no pressurisation of safe paths, fire hose reels provided, emergency lighting in exitways, fire hydrant system
2006/52 - Two towers connected through lower carparking levels 18 Turner Street 17-19 Waverley Street	14 13	14 stories above 3 levels of basement car parking, 6 apartments on ground floor and 7 on all above Ground level has managers office, rubbish area, and 2 apartments. Levels 1B-10B have 5 apartments, level 11B has 7 apartments	97 59	41 38.4	Single escape route, dual ”Class B” water supply, 1200 mm egress width of stairs Type 8 voice communication system

Table 11.1: Summary of the single means of escape building configurations which went through determinations in New Zealand in 2005 and 2006. (FR - fast response, FS - fire service)

In the 2 Forest Laneway fire, an occupant on the fifth floor of a 30 floor apartment building noticed a smouldering fire on the couch in his apartment living room at 5:00 am. After an attempt at extinguishing the fire, he opened the balcony door in his apartment and left his apartment, also leaving his front apartment door open. There were six victims found in the upper staircases of the building, along with seven occupants who were treated for smoke inhalation. In this fire there was an additional fire door between the hallway on each floor and the stair shaft.

Fire safety system enhancements in the building to compensate for the single means of escape included upgrading the sprinkler system, aspects of the fire rated construction, and implementing a staged evacuation scheme with a voice communication system. The sprinkler system upgrades included a dual street main water supply, fast response sprinkler heads on apartment levels, and a "Type 2" fire service connection. The masonry construction was specified to give a 60/60/60 fire resistance rating between apartments, the apartments and the atrium, and the walls surrounding the central services duct. This was an upgrade from the minimum 30/30/30 fire resistance considered to be achieved with plasterboard walls in the compared compliant building. The staged evacuation scheme and voice communication system were not considered in the comparative analysis.

The sprinkler effectiveness was considered to be composed of reliability and efficacy. Sprinkler efficacy was considered to be 0.998 with no uncertainty for both compliant and alternative building designs, although the determination document mentions that fast response sprinkler heads are one of the improvements in the alternative solution which would be expected to have some influence on efficacy. Sprinkler reliability was assumed to be a uniform distribution from 0.994 to 1 for the alternative building and from 0.992 to 0.998 for the compliant building. The increase in reliability was attributed to the difference between a single town main "Class C" supply with diesel pump for the compliant building and a dual supply sprinkler system. Although the building had been constructed at the time of the determination, there appeared to be some confusion as to the nature of the dual sprinkler supply: the determination document states that it was a dual street main water supply, while the supporting documentation for the increase in reliability states that it was a "Class A" water supply, with a mains water supply using an electric pump and a tank water supply using a diesel pump. The building layout plans in the determination document do not identify the location of a water tank for sprinkler system supply.

The fire separation effectiveness was not decomposed into reliability and efficacy. A single parameter was used to consider the effectiveness of the walls and doors to control the spread of smoke and flame. For the walls, the increased difficulty in penetrating masonry compared to a frame wall with plasterboard was considered to increase the mean effectiveness from 0.88 to 0.92. These mean values were derived from BS PD7974-7, which gives probabilities of 0.75 and 0.65 for masonry walls and partition walls to achieve 75% of their fire rating, respectively[4]. It was assumed that the failures occurred at penetrations, which failed either because they had not been stopped or had been improperly stopped. It was then assumed that two thirds of these failures were due to improperly stopped penetrations, and one third were due to the penetration not being stopped at all. As smoke spread is a different criterion than the wall meeting its fire resistance, the improperly stopped penetrations were then neglected for the control of smoke spread. Hence the mean values were calculated:

$$P(\text{masonry wall controls passage of smoke}) = 1 - 1/3 \times 0.25 = 0.92 \tag{11.1}$$

$$P(\text{lightweight wall controls passage of smoke}) = 1 - 1/3 \times 0.35 = 0.88 \tag{11.2}$$

Uncertainty in these values was considered by applying a normal distribution with the means mentioned above and a standard deviation of 0.01 for both cases, with no further justification on the uncertainty.

The effectiveness of doors from apartments into corridors was considered to be 0.89 while doors from corridors into stairs was considered to be 0.85, due to their different usage characteristics. Uncertainty was added by using normal distributions with standard deviations of 0.05, and truncated at 1.0.

In the initial risk assessment, the stairway pressurisation system effectiveness was given an efficacy factor of 0.92. Monte Carlo simulations were used to examine scenarios where leakage reduced air velocity across the door to the apartment of fire origin below 0.8 m/s for 10 seconds or more. While the Monte Carlo simulation did not produce any ineffective cases, a failure rate of 0.002 was assumed. Separate simulations also looked at the possibility that the stairway pressurisation system was overwhelmed if the apartment of fire origin was on the windward side of the building during high winds with an external opening. While it was stated that a number of Monte Carlo simulations for adverse wind conditions resulted in failures, the rate was not reported. Ultimately a 0.08 ineffectiveness rate was selected for adverse wind conditions, giving a combined inefficacy rate of 0.082 and thus an efficacy rate of 0.92. Pressurization system reliability was calculated based on numbers reported by Zhao[7], although the fire damper failure rate was reduced from 0.086 to 0.06 on the basis that there were fewer dampers in the building than normal. The reliability was calculated to be 0.91, giving an overall effectiveness of 0.84 for the stairway pressurisation system. Uncertainty was considered by applying a normal distribution with a standard deviation of 0.1, truncated at 1.0.

As a result of the determination process, a second risk assessment was completed, and considered the uncertainty in the stairway pressurisation system to be underestimated in the first risk assessment. The second assessment used a uniform distribution from 0.5 to 0.9 for stairway pressurisation.

Another expert who was asked to review the determination information estimated effectiveness values of 0.94 for the “Class C” single supply building C sprinkler system, and 0.97 for the building A “Class B” dual supply sprinkler system. Lightweight 30 minute fire resistance walls were given an effectiveness of 0.7 and 60 minute masonry walls were given an effectiveness of 0.8. The effectiveness of the stair pressurisation system was assumed to be 0.1. No justification was given for these values other than that they were educated estimates. This expert used BRANZFire to model the effectiveness of the stair pressurisation system.

The comparative analysis conducted for determination 2005/109 did not consider time dependent effects. Non time-dependent event trees were used to compare the risk between the alternative solution building and the compliant design, although specific scenarios were modelled as a function of time. A sensitivity study was conducted using standardized b coefficients which showed that the risk outcomes were most sensitive to the sprinkler system effectiveness, followed by the pressurisation system and fire barriers.

The conclusion of determination 2005/109 states that the building did not comply with clause C2 of the building code. The risk margin calculated in the risk assessments was less than the required 75%. However, as the building consent had already been issued and the building was completed, modifications to the consent requirements were made, including greater commissioning requirements for the smoke pressurization and a limitation on the consent for Purpose Group SR occupancy only (attached and multi-unit residential dwellings). At the time of the determination the building was being used as a Purpose Group SA occupancy (spaces provided for the use of people who will be transient and reside for a temporary period, typically not more than 90 days).

11.1.2.2 Subsequent determinations

The approach taken in the five subsequent single means of escape determinations was similar with respect to the effectiveness of the proposed fire safety systems. A summary of the details of each of the determinations is included below followed by a discussion of how the fire safety system effectiveness was considered. The DBH determination documents should be referenced for a more complete description of the determinations.

The building considered in determination 2005/134 had 16 levels, with the four bottom levels consisting of the basement, three levels of parking and retail tenancies, and the top 12 tower levels containing eight or ten apartments. The tower was split with a concrete wall, and each side was mirrored, with a single stairway and two lifts. The maximum escape height was 43.6 m. The fire safety features that were considered to make up for the single means of escape were a secondary electric pump for the sprinkler system, pressurisation of the stairways, and a staged evacuation scheme including voice communication. The consenting process for this building was to proceed in stages. At the time of the determination, two stages of consent had been issued: one for the overall building configuration, and the second for foundations and drainage. Construction was underway when the application for the third stage of consent which included the architectural and services content was lodged with the territorial authority on March 3, 2004. The territorial authority rejected the application due to the single means of escape in early 2005, leading to the determination. The outcome of the determination was that the building commplied with clause C2 of the building code[8].

Determination 2005/168 involved a 15 level residential high-rise building. The lower ground floor had service rooms and seven apartments, the second level had an entry lobby, mail area, two office spaces, a cafe and 12 apartments. All the upper levels contained 16 apartments with the exception of the third level which contained 15 because the area above the second level cafe kitchen was void. The features of the proposed building that were intended to compensate for the single means of escape included a dual "Class A" water supply for the sprinkler system, pressurisation for the stairwell, and a "Type 8" voice communication system. This building was not under construction at the time of the determination, and the outcome of the determination indicated that the proposed building did not comply with clauses C2 and C3 of the building code[9].

The proposed building that was examined in determination 2005/169 included two towers above four common levels of basement car parking. One of the towers was four storeys above ground level, with the ground level including services, an office, the lobby, and two apartments. All other levels in the towers contained six apartments. Bridge connections joined the first four storeys of the two towers above ground level. The features that were identified as compensation for the single means of escape from the upper levels of the 12 storey tower were a sprinkler system with a dual "Class B" water supply, the primary supply consisting of a tank boosted by a diesel pump. The secondary supply was to be a reticulated supply boosted by either a diesel or electric pump. The stairway was to be pressurised and a Type 8 voice communication system was provided. The outcome of the determination was that the proposed building did not comply with clauses C2 and C3 of the building code[10].

The building which resulted in determination 2006/34 was originally an office building which had been converted to residences. The maximum escape height of the original building was less than 25 m so it did not require two means of escape. The determination was a result of proposed modifications to add two storeys to the building, which increased the maximum escape height to 29.25 m. The features that were proposed to compensate for the single means of escape included a dual "Class A" water supply for the sprinkler system and a stairway pressurisation system. The determination found that the alternative solution proposed met the requirements of clauses C2 and C3 of the building code[11].

The final single means of escape determination, 2006/52, involved the proposed design of two residential high-rise towers of 13 and 14 storeys above ground level and connected by lower carparking levels. Features considered to compensate for the single means of escape were a dual "Class B" water supply for the sprinkler system, an increase in the egress stair width from 1000 mm to 1200 mm, and a Type 8 voice communication system. The proposed design of the towers was determined to not meet the requirements of clauses C2 and C3 of the building code[12].

A nominal value of 0.95 was used for the sprinkler reliability for buildings with single "Class C" supply sprinkler systems. This value was chosen based on guidance from PD7974-7(2003). The enhancement of a secondary electrical pump was estimated to increase the nominal sprinkler system reliability by 0.005 to 0.955. Feeney's conclusion that the reliability of the sprinkler system depended on the pump much more than the availability of water from reticulated systems was referenced[13] but was recommended to be used with caution. For designs with dual "Class A" water supplies, combining a reticulated supply with a tank supply, the nominal sprinkler system reliability was increased to 0.96. Uncertainty in sprinkler system reliability for both buildings was considered by applying a uniform distribution from .02 below to .02 above the nominal reliability value. Efficacy was again considered with a 0.95 reduction in sprinkler system effectiveness, with no consideration of uncertainty.

The reliability of smoke alarm systems was estimated with a mean of 0.90, using the value given in PD7974-7(2003). A normal distribution with a standard deviation of 0.05 was used to account for uncertainty. An efficacy factor of 0.90 was used with no uncertainty considered. The smoke alarm was not a factor in the comparative analysis outcome for any of the determinations because the same system effectiveness was considered for all designs.

Barrier reliability was found using fault tree analysis and data from PD7974-7(2003). Mean reliabilities of 0.42 and 0.36 were derived for masonry and lightweight construction, respectively. These values were deemed to be lower than expected, and since building A only had two barriers while building C had three, the underestimation was considered to comparatively favour building A. Therefore, adjustments to the values given in PD7974-7(2003) were made resulting in reliability values of 0.65 and 0.58. Uncertainty was considered with uniform distributions .10 above and below the mean values. Efficacy was considered to be 1.0, therefore it did not affect the results.

The reliability of the stair pressurisation was assumed to have a mean of 0.90, which was taken from PD7974-7(2003). A uniform distribution from 0.50 to 1.0 was assumed for the stair pressurisation efficacy.

Sensitivity analysis was done using a proprietary algorithm to calculate the standardized b coefficients. It was found that the risk outcome was most sensitive to partition barrier effectiveness, followed by the sprinkler system effectiveness and pressurisation effectiveness.

11.1.3 Ramifications for this research

The examples listed above where probabilistic methods were used for fire safety applications in New Zealand demonstrate the lack of knowledge regarding the expected performance of fire safety systems for risk purposes. In many cases, even if mean values of effectiveness are based on existing data, they are tweaked by "expert judgement" which is in all cases subjective[14]. One of the major issues identified is how effectiveness inputs should be modified with changes to the systems installed; for example, a change from a single water supply for the sprinkler system to a dual supply. The goal of this project is that B-RISK will be a useful tool to resolve these issues in the future.

11.1.4 140 William Street case study

A risk-informed approach in evaluating the fire safety of an office building was completed for the 140 William Street building refurbishment in Melbourne, Australia in 1992[15]. The building has 41 storeys in total with 37 occupied as offices. One of the requirements of the refurbishment was to remove asbestos-based fire protection material from the floor slab soffits and supporting beams. In addition, the deemed-to-satisfy (DTS) building regulation requirements at the time of the refurbishment required a sprinkler system designed for the Ordinary Hazard (OH) classification, while the existing system was designed as Extra Light Hazard (ELH). The proposed refurbishment did not include replacement of the removed fire protection material or an upgrade of the sprinkler system to make it adequate for the ordinary hazard classification.

Fire risk was compared in three building configurations: the existing building, the proposed refurbished building, and a similar building configuration that met the deemed-to-satisfy requirements (known as the "Building Code of Australia" (BCA) configuration in the original report, called the "deemed-to-satisfy" (DTS) here). The fire brigade and occupant response was considered in the analysis.

The ELH sprinkler system in the existing building had sprinkler heads typically installed 4.6 m apart. The ceiling spaces were not sprinklered. Two separate towns' mains supplied the sprinkler system, with individual risers for four adjacent floors. Each riser had a stop valve. Neither the riser stop valves or the main stop valve for the entire system were monitored. Pressure to supply water above the 8th floor was provided by electric pumps backed up by diesel pumps, with separate pressure switches. The electricity supply for the building was not provided by a utility but was rather generated in the building by diesel and natural gas generators. The existing building sprinkler system did not have a fire service water connection. Flow switches on the sprinkler system risers were directly connected to the fire brigade. Individual floor flow switches were connected to the building alarm system but not to the fire brigade.

The OH system required by the Australian DTS document at the time of the refurbishment for a building of similar configuration to the 140 William Street building decreased the allowable sprinkler head spacing to 3.5 m. Monitored riser and main valves, ceiling space sprinklers, and a fire service water connection were required. The DTS requirements did not include floor flow switches.

For the refurbished building, it was proposed to add monitored floor isolation, riser, and main valves to the existing system, and a gravity water supply to supplement the two towns' main supplies. Solenoid valves on each floor were provided to allow required weekly water availability and flow switch operation testing on each floor. Fire brigade intervention was included in the sprinkler effectiveness for the DTS and refurbished buildings due to the inclusion of a fire service inlet which would allow the sprinkler supply pressure to be boosted by an arriving fire appliance.

The DTS and refurbished building designs included sandwich pressurisation. The pressurisation system effectiveness was estimated at 90%. The existing building had smoke detection in the return air ducts only, while the DTS and refurbished building added detectors to the top of the stairwells and the office side of the fire doors separating the two areas.

The probabilities of individual events occurring were assigned by using uniform distributions over time. These distributions were then sampled using a Monte Carlo procedure and combined in the event tree to determine the time to detection and times to untenability for the simplified modelled enclosures.

The analysis used a measure of expected deaths per occupant per year to conclude that the DTS building was safe (4.4 x 10^{-8} expected deaths per occupant per year without maintenance, 3.2 x 10^{-8} with maintenance), the existing building was safer (7.7 x 10^{-9} expected deaths per occupant per year), and the refurbished building was safest (1.5 x 10^{-9} expected deaths per occupant per year with extra fire doors, 1.6 x 10^{-9} without extra fire doors). It was presumed that the stairwell pressurisation system was the primary factor in the increase in safety between the existing building and the refurbished building.

11.2 High intensity residential fires in Alberta, Canada

Light timber residential construction with combustible cladding led to major fires in Alberta, Canada in the late 1990s and 2000s where they were known as “high intensity residential fires.” In some cases, these fires occurred in large buildings despite the presence of installed fire safety systems. The author’s interest in the performance of fire safety systems stemmed from involvement in the investigation of one such fire in 2009 where sprinklers and passive fire protection features were key factors in the development of the fire. The inclusion of this case study is primarily due to the author’s personal involvment in this investigation.

The building involved was a 4 storey timber frame seniors’ assisted living condominium complex, as shown in Figure 11.3. The 4 storey sleeping household areas of the building were separated into two fire cells by a masonry firewall. A two storey wing housed a commercial-style kitchen, dining area, and recreational facilities. The kitchen and dining area were separated from the rest of the structure by another masonry firewall. The sleeping areas of the building were sprinklered to NFPA 13R[16], which did not require the attic space to be sprinklered.

The fire consumed the roof and unsprinklered attic space of one of the 4 storey fire cells containing the sleeping occupancy areas. Fire spread to the other fire cells was limited by the masonry firewalls. The occupants of the building all escaped

Figure 11.3: Seniors' complex fire, Alberta, Canada, 2009 (Photo source: Edmonton Journal[17]).

without injury; notable because the fire occured at 3:30 am and many occupants had restricted mobility. Damage to the occupied space of the building was limited to primarily water damage from firefighting efforts and activated sprinklers positioned below the ceiling on the top floor. However, the building was a complete loss due to the effects of the water on the building structure.

The systems involved in the fire performed as expected in terms of life safety objectives, but failed to protect property. From a social standpoint, the lives of many of the occupants were impacted by the loss of necessities such as medications, mobility assistance devices, as well as the loss of personal items of sentimental value, such as letters, photographs, and other documents. As a result of this fire and other high intensity residential fires[18] in Alberta, the Alberta Building Code was changed to require sprinklers installed in the attic space and other concealed spaces of 4 storey residential timber frame buildings, among other changes[19].

While it does seem that some change was necessary, it did not appear that a risk-informed approach was taken to evaluate the costs and benefits of changing the building regulation requirements. There was no analysis to determine if the changes would either be sufficient or go too far in modifying the fire risk based on the increased cost of construction and societal fire risk objectives. It was observed by the author that evaluating the effectiveness of fire safety systems was uncertain and open to interpretation, even in a large loss fire where substantial fire investigation resources were deployed by multiple parties.

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CHAPTER 12

USE OF THE B-RISK MODEL IN RISK-INFORMED FIRE SAFETY DESIGN

12.1 Introduction

The purpose of this chapter is to demonstrate how the B-RISK model might be used to make decisions in risk-informed fire safety design. Two of the case studies discussed in Chapter 11 will be used as the basis for the buildings considered; the first building design that went through the single means of escape (SME) determination process and the 140 William Street building. Where applicable, particularly for the 140 William Street building, New Zealand regulations and standards are applied instead of the documents used for the actual building designs since these examples are for illustrative purposes only and B-RISK is being developed primarily for use in New Zealand, although ideally it will be useful in other jurisdictions as well.

The focus of this chapter is on the use of the safety systems aspects of B-RISK. Discussion of other aspects such as the design fire generator are limited. Fuel configurations in the simulations were simplified; for example, in the second office building case study, office workstations were treated as a single fuel item and are not broken down into their components. Uncertainties in the mass, heat release rate, and ignition properties of items were not considered, although uncertainty in these parameters is likely to be large and significant in real scenarios.

The B-RISK model is used to do a comparative analysis between alternative designs. The deemed-to-satisfy building designs and the alternative designs from the original case studies are compared, as nearly as practicable. Since this research only considers fire development, time to untenability was used to compare the designs. The C/VM2 tenability criteria were used as the basis for comparison. Since internal fire development was the only aspect considered, exterior fire spread, occupant response, and fire service response were not considered. Also, structural fire resistance is not considered; thus, the main objective of the 140 William Street study which was to determine if it was necessary to apply floor slab and beam fire protection is not included. Other fire risk objectives such as property protection are not considered in this analysis.

12.1.1 General model parameters

The interior temperature was set as a uniform distribution from 15^{o}C to 25^{o}C, the exterior temperature was set as a uniform distribution from 2^{o}C to 29^{o}C, and the relative humidity was set at 50%, approximately representing New Zealand conditions. For an actual building design, site weather data should be used to estimate these parameters.

CO yields were calculated using the built-in model that estimated the yield based on the global equivalence ratio (GER)[1]. Well-ventilated soot yields were entered and the B-RISK GER model was used to adjust for reduced ventilation. B-RISK release version 48 was used for this chapter.

12.2 Common material properties

Three generic materials were used to represent the objects for the two buildings. Common material properties used among the items are listed in this section.

12.2.1 Ignition

The FTP ignition properties used are summarised in Table 12.1. The ignition properties were all based on auto ignition data.

For all items, a uniform distribution from 0.3 to 0.4 was used for the radiant loss fraction.

Target ignition parameters	ABS[2]	MDF[2]	PU/Polyester[3]
FTP ($kWs^{1/n}/m^2$)	14126	2913	427
n	1.8	1.3	1
$\dot{q}''_{cr}$ (kW/m^2)	25	35	22

Table 12.1: Common auto ignition properties used for all items modelled.

Parameter	Units	Mean	Standard Deviation	Lower bound	Upper bound
h_c	MJ/kg	14	1	12	16
Soot yield	kg/kg	0.015	0.002	0.01	0.02
CO_2 yield	kg/kg	1.3	0.15	1.27	1.33
χ_{rad}		0.35	0.046	0.3	0.4

Table 12.2: MDF properties estimated from SFPE handbook data on wood products[5].

12.2.2 Foam soot yield

For foam based items, the lognormal distribution described by Robbins and Wade[4] based on 1995 CBUF data with an outlier removed was used. The log transformed mean was -3.93 and the standard deviation was 0.78.

12.2.3 MDF properties

For the MDF-based object properties, data from the SFPE handbook for wood products was used[5]. A summary of the relevant parameters is listed in Table 12.2.

12.2.4 Criteria used to evaluate the designs

The criteria used in this analysis to compare the alternate and deemed-to-satisfy building designs is primarily the time to untenability in the stairwells and a remote apartment, although tenability in the fire compartment is briefly discussed as well. Visibility and the fractional effective dose (FED) of carbon monoxide and thermal radiation are used as the criteria as specified in C/VM2. Fractional effective dose measures the cumulative effects of the toxic or thermal insult on an occupant over time. A fractional effective dose of one corresponds to the onset of incapacitation or death of an average person. The untenable limits are 10 m visibility and 0.3 FED_g

and FED_{th}, evaluated at a height of 2.0 m. The FED values are calculated from the time of fire ignition in each room, so will not be representative of an occupant's exposure while travelling through the building during the course of the fire, and is for illustrative purposes only.

The time to untenability represents the available safe egress time (ASET) for an occupant. The required safe egress time (RSET) is not considered here because it is currently beyond the scope of the model. The total simulated time for the B-RISK model was 600 s for convenience as this is an illustration of the use of B-RISK only. For a full risk analysis including occupant behaviour which is necessary to determine the time required for the occupants to egress the building, the simulated time would need to be sufficient to encompass the longest probabilistic RSET duration.

12.3 SME Building

12.3.1 Principal building characteristics common to both designs

The first scenario is an 18 storey high rise apartment building. The first floor has a rubbish room, fire services room, entrance lobby, and a truck dock. The second floor had three apartments, an office, and a plant room. Each floor from 3 to 18 contained 6 apartments, for a total of 99 apartments in the building. All apartments were 9 m long x 3 m wide for a floor area of 27 m^3, with 3 m ceiling height. The four corner apartments on each floor were configured as studio apartments and the two central apartments were configured as one-bedroom apartments. An elevation view of the building is shown in Figure 12.1.

Apartments in the building are intended to be used as short stay serviced apartments. However, they also can be leased out as unfurnished apartments, so both options will be considered. A serviced apartment was considered to have specific fuel packages in constant locations, whereas an unfurnished apartment was considered to have a variable fuel load magnitude and location.

12.3.2 Proposed alternative building fire safety design

A plan view of the proposed design typical layout for levels 3 to 18 is shown in Figure 12.2. The doors from the apartments open directly onto the central atrium

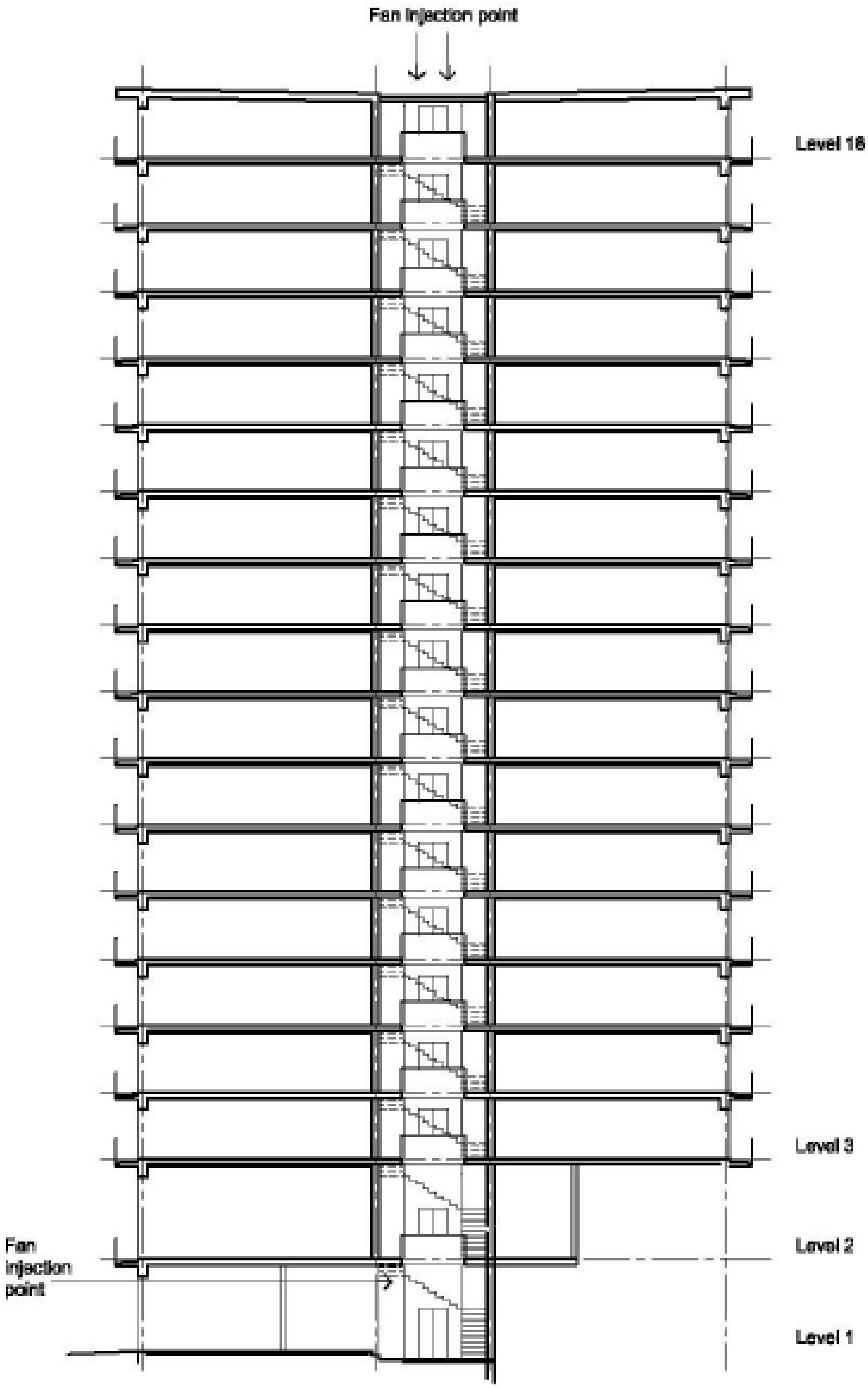


Figure 12.1: Elevation view of scenario 1 building (from DBH determination 2005-109[6].

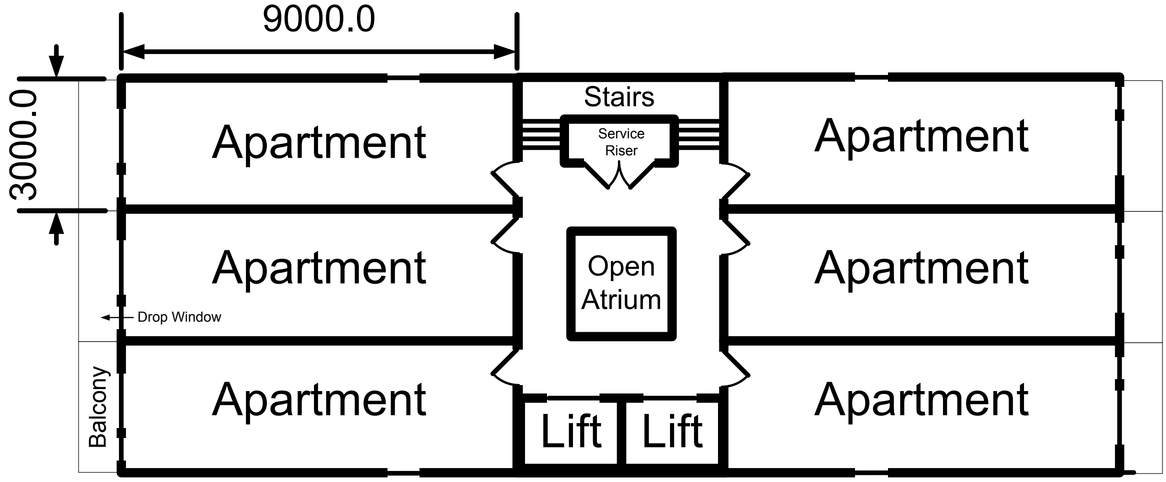


Figure 12.2: Typical level plan view of scenario 1 proposed building (from DBH determination 2005-109[6].

which has a walkway around an open vertical column with open stairs on one side and two lifts on the other.

As discussed in Chapter 11, the proposed design of the SME building did not meet the C/AS1 deemed-to-satisfy requirements because the maximum escape height exceeds 25 m and there is a single means of escape. Other changes from the deemed-to-satisfy requirements include an enhanced sprinkler system with a dual towns' mains/on-site tank water supply, apartment level fast response sprinkler heads, and a manual fire alarm system connected to the NZFS; 60/60/60 fire rated construction between apartments, the apartments and atrium, and service duct walls compared with the 30/30/30 C/AS1 requirement; and a Type 8 voice communication system with staged evacuation. The evacuation system will not be included in this analysis since the human response is not included; nor is the fire resistance rating considered.

12.3.3 Comparison deemed-to-satisfy building fire safety design

The comparison building has a similar design to the proposed building but with two means of escape. A typical floor layout can be seen in Figure 12.3. While a Type 7e alarm (sprinkler system with smoke detectors and manual call points, local alarm in sleeping firecells) and 30/30/30 fire resistance rating between fire cells were re-

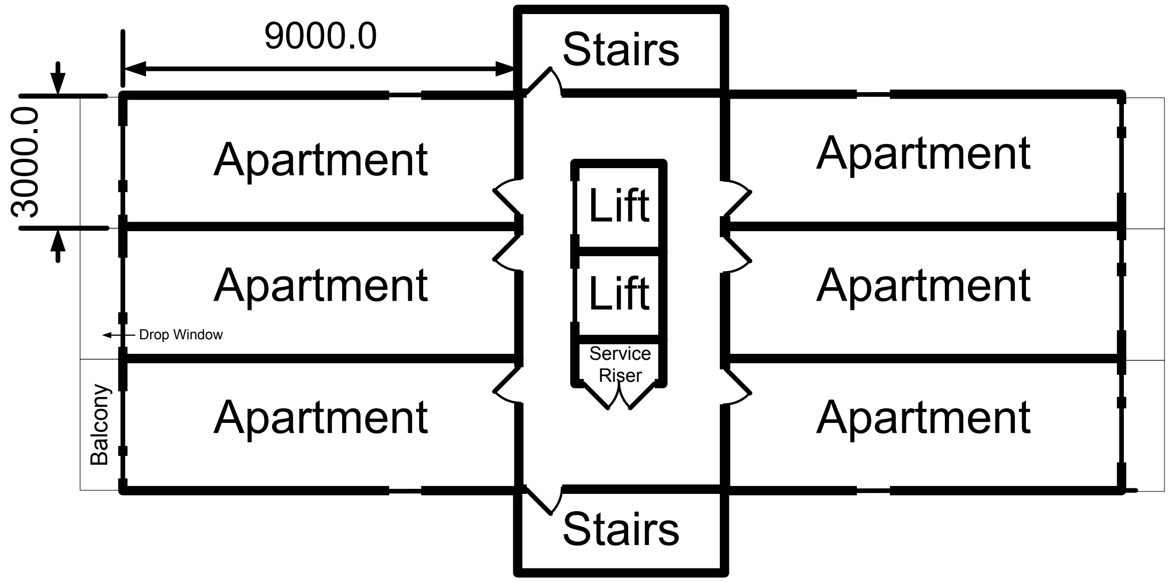


Figure 12.3: Typical level plan view of scenario 1 compliant building.

quired, this building does not include the sprinkler system and fire rated construction enhancements of the proposed building. As short stay serviced apartments, the relevant C/AS1 purpose group was SA (*spaces provided for the use of people who will be transient and reside for a temporary period, typically not more than 90 days*), while for use as longer term leased apartments the appropriate C/AS1 purpose group was SR (*attached and multi-unit residential dwellings*). The determination noted that there was some discussion regarding the appropriate purpose group for the deemed-to-satisfy comparison building and ultimately the SR purpose group was utilized. The SA purpose group was required to have pressurised safe paths, air handling system smoke control, and a voice communication system for escape heights exceeding 46 m, which the SR purpose group was not required to have[7].

12.3.4 Fire doors

Fire doors in the building models include the apartment doors, outside door and shared means of escape doors in the comparison building. Each door was represented by two vents; one representing leakage and one representing the open or shut status of the door. For security and privacy reasons, apartment doors would normally be shut at all times other than when occupants are moving through them. They may be propped open for moving furniture or for cleaning staff in the case of serviced apartments. In case of a fire, the door may be left open by an egressing occupants or held open by an incapacitated occupant, if they should succumb in the doorway. An outside door was included for each stairwell and they were considered to be open for the duration of the fire, as they would be opened as egressing occupants passed through them. The opening and closing of fire doors during occupant egress as discussed in Chapter 9 was not included since occupant response was not simulated and B-RISK does not currently have the capability to include vents opening and closing during egress.

12.3.5 Sprinkler system layout

As the building is hypothetical, a characteristic water supply curve was assumed, shown in Figure 12.4. The water supply curve was chosen to allow the hydraulic requirements to be met with reasonable pipe sizing while still allowing the critical threshold to be exceeded if more sprinklers were activated than required by the sprinkler standard. For actual design, the measured water supply curve should be used. Since the building had more than 3 storeys the use of NZS4515: Fire Sprinkler Systems for Life Safety in Sleeping Occupancies[8] was not an option, so the sprinkler system was designed to NZS4541:2007[9]. As a residential occupancy, the sprinkler hazard group was extra low hazard (ELH) per NZS4541:2007 Table 2.1.

Based on the 3 m x 9 m apartment configuration, sprinklers were located on the long dimension centreline 2.25 m from each end, to provide 13.5 m^2 coverage each, as shown in Figure 12.5. No more than two sprinklers could be activated in the apartment fire scenario considered here due to the compartmentalisation, although the hydraulic design was specified to the minimum required in NZS4541:2007 for ELH, at least 4.1 mm/min or 50 kPa supplied to the most remote four sprinklers. Both designs used 68^{o}C activation 15 mm sprinklers with $8.0\frac{L/min}{\sqrt{kPa}}$ K-factor, with standard response glass bulbs in the comparison building and quick response glass bulbs in the alternative building. To meet the hydraulic requirements, 32 mm pipe was specified throughout. This configuration satisfied the 80% supply flow characteristic criteria using the previously defined hydraulic supply curve. The sprinkler thermal response parameters used are shown in Table 12.3. The parallel sprinkler orientation RTI distributions from Tsui et al[10] were chosen as they were more conservative than for the perpendicular orientation.

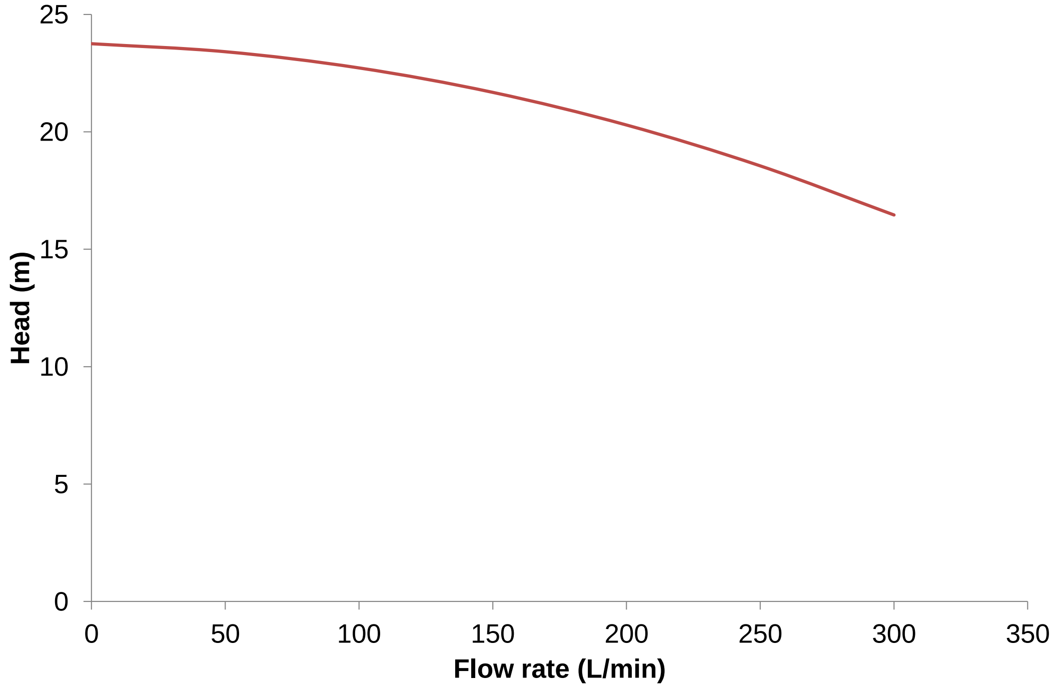


Figure 12.4: Hypothetical water supply for the SME building, measured at the riser on the most hydraulically remote floor.

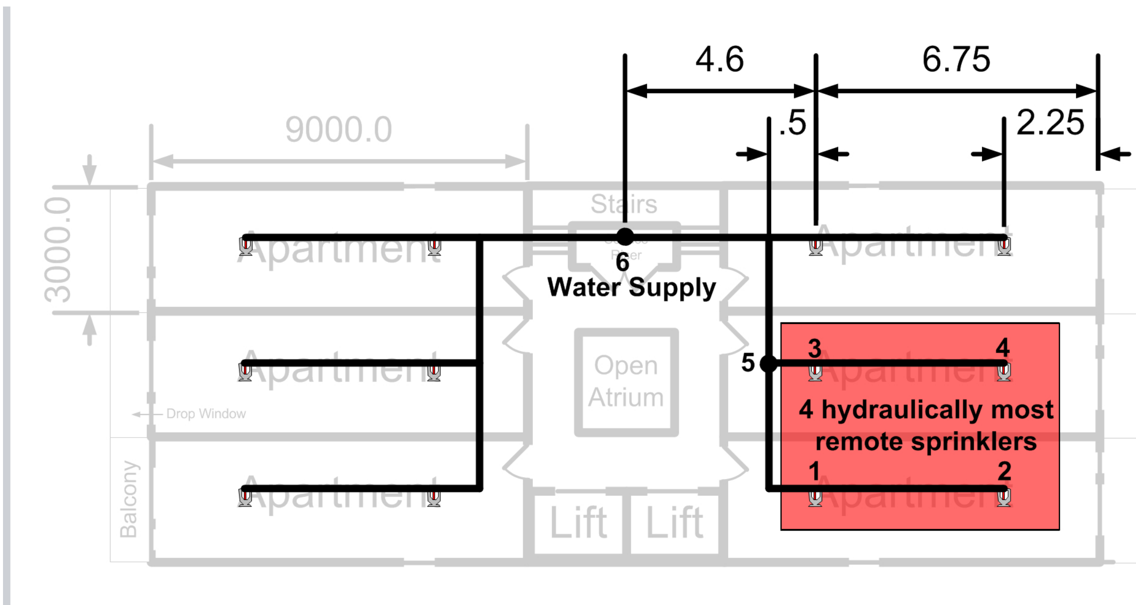


Figure 12.5: Sprinkler layout for one floor of the SME building. Nodes used for the hydraulic model are shown. All piping 32 mm diameter, dimensions shown in m.

Parameter	Distribution Type	Distribution Parameters		Source
Standard RTI	Normal	μ=93.4(m s)$^{1/2}$	σ=4.4(m s)$^{1/2}$	[10]
Quick RTI	Normal	μ=39.1(m s)$^{1/2}$	σ=2.9(m s)$^{1/2}$	[10]
C Factor	Normal	μ=0.44 (m/s)$^{-1}$	σ=0.01 (m/s)$^{-1}$	[10]
Actuation T	Normal	μ=72^{o}C	σ=0.655^{o}C	[11]

Table 12.3: Distributions for the uncertainty in sprinkler parameters, used for both scenarios.

12.3.6 Sprinkler system effectiveness

The distribution for sprinkler reliability reported in Chapter 4 with a mean of 95% and a standard distribution of 1.6% was used for the single water supply sprinkler system in the comparison building. No fire incident data has been identified that allows the effect of sprinkler water supply to be isolated, including the NZFS data, but it was assumed that most installed sprinkler systems have single supplies. The data in Chapter 3 indicates that the reduction in water supply failure per demand ranges from approximately 1 fire in 2000 to 1 fire in 100 from data reported by Brammer[12]. To estimate the increase in reliability due to a dual water supply, a uniform distribution from 5 x 10^{-5} to 1^{-2} was added to the reliability distribution for the comparison building. This resulted in a mean reliability of 95.5% with a standard deviation of 1.63%, shown visually in Figure 12.6. The distribution reported in Chapter 4 for sprinkler efficacy was used for the sprinklers in both buildings. The upgrade in sprinkler system water supply between the two building designs would not affect sprinkler efficacy.

12.3.7 Passive building elements

As this study was conducted prior to the door reliability data collection described in Chapter 9, door reliability for the remote and fire apartments was estimated using the residential door data discussed in Chapter 8 from the 1970 UK study[13]. A normal distribution with a mean reliability of 0.83 and a standard deviation of 0.0038 was estimated from a binomial distribution with n = 9887 and p = 0.83, since B-RISK did not allow binomial distributions as a distribution type at the time this work was completed.

The door size was 0.8 m wide x 2 m tall. Door leakage was estimated as a vent with a uniform distribution for the width from 0.00025 m 0.023 m over the door

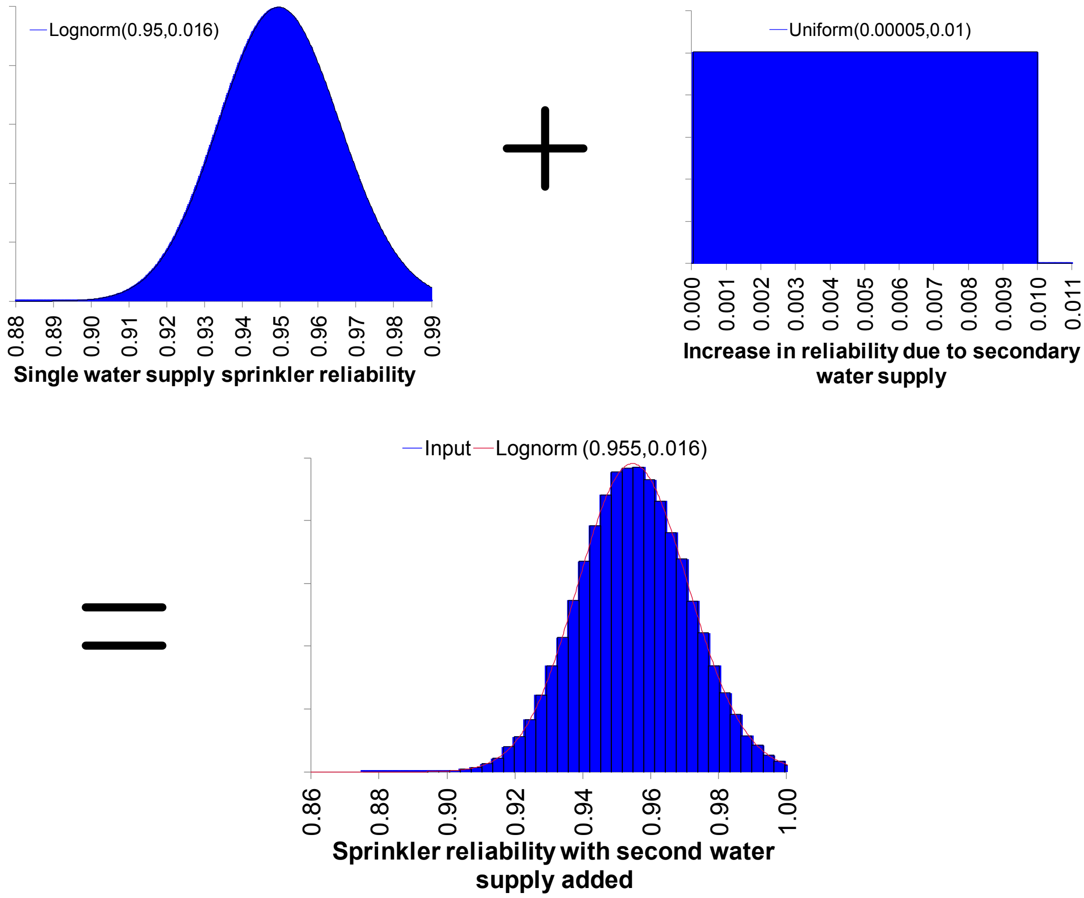


Figure 12.6: Distributions used for sprinkler system reliability for the B-RISK risk-informed examples. The first number in parenthesis for the log normal distributions is the mean and the second is the standard deviation. The numbers for the uniform distribution represent the upper and lower limits.

height of 2.0 m. The bounds of the uniform distribution were based on tight and loose door leakage as reported by Klote and Milke[14] and described in Chapter 8. The stairwell leakage was estimated by adding the leakage for all of the apartment doors to the wall leakage reported by Klote and Milke.

An additional door was included on each floor that was not the fire floor or the floor with the remote apartment to provide additional flow outlets for the stairwell pressurisation fan. Since apartment doors opened directly onto the atrium in the alternate building, the reliability was increased to a mean of 0.95 to account for security, on the assumption that people would be reluctant to leave their front door open when they left their apartment.

A large window representing the patio door to the balcony of 2 m x 2 m was modelled using the same distribution for the probability that it was open at the time of the fire as the fire compartment door.

12.3.8 Smoke management systems

The determination is not clear whether stairwell pressurisation was required in the deemed-to-satisfy building. It was not listed in the determination as an additional safety feature in the alternative building; however, the risk analysis that was performed did not include pressurisation in the deemed-to-satisfy building design. Therefore, the deemed-to-satisfy building was run in B-RISK with and without stairwell pressurisation to determine the sensitivity of the time to untenability to the presence of the pressurisation system. For the comparisons to the alternative building, the deemed-to-satisfy building without the stairwell pressurisation system was used.

In the B-RISK model, the fans were initiated by a smoke detector placed in the stairwell. A single fan was used for each stairwell, placed at the top of the stairwells and using fan curve option with a flow rate of 10 m^3/s. While the building design called for four fans, three at the top and one at the bottom, they were not individually modelled because B-RISK can not model multiple fans in a compartment with varying elevations and flow characteristics[1]. The design pressure limit was set at 50 Pa. A uniform distribution for the pressure limit from 25 Pa to 75 Pa was used, based on the recommendation from Klote and Milke discussed in Chapter 10. Uniform reliability distributions were also used for the smoke detection system (limits 0.9 and 0.99, based on the simple system fault tree analysis by Gravestock[15]) A uniform distribution for the fan reliability (limits 0.72 to 0.97) and for the overall smoke management system (limits 0.43 to 0.87) based on Gravestock's[15] analysis, due to a lack of better information on reliability uncertainty.

As described in the original building design, a drop down window activated by the smoke detector in the fire compartment was included to provide a flow path for the fire products to exit the building. The window size and location in the original design was not specified so an estimate of 1 m x 1 m at a sill height of 1 m was used.

The distribution in Chapter 10 for optical density at alarm for a photoelectric smoke detector with flaming fires was used for both smoke detectors. Photoelectric detectors were chosen arbitrarily for these examples, for actual building design the specified detector type should be used.

12.3.9 Design fires

Three types of apartment design fires were considered: the first used a randomly placed t^2 fire, the second used the item-to-item design fire generator with fixed item locations representing a short stay furnished apartment, and the third used the item-to-item design fire generator with random item placement representing a long term leased apartment.

12.3.10 Apartment fuel package configuration for item-to-item fire spread design fire

Two potential fuel package configurations for the design fire generator were considered: one approximating a short stay furnished apartment and one approximating a long term leased apartment.

12.3.10.1 Short stay furnished apartment

The furniture and contents arrangement for a short stay apartment was considered static, and the potential for additional fuel load from personal contents was considered minimal. A typical apartment furniture layout was estimated from diagrams viewed on the building website, shown in Figure 12.7[16]. The studio apartment configuration with one sofa and a TV was used. Typical contents included a king-sized bed, bedside table, wardrobe, dining set, three seat upholstered foam couch, TV and stand, and coffee table. It was noted on the website that cots and high chairs are available for rent, but these items were not considered in the analysis. This is an example of fuel load uncertainty that could have been considered. The layout is shown in Figure 12.8. Note that nothing was placed between the wardrobe and the right end of the apartment because the bathroom was located there and which was assumed to contain negligible quantities of exposed combustible items.

Figure 12.7: Short stay furnished apartment item configurations, shown in diagrams from the building website[16].

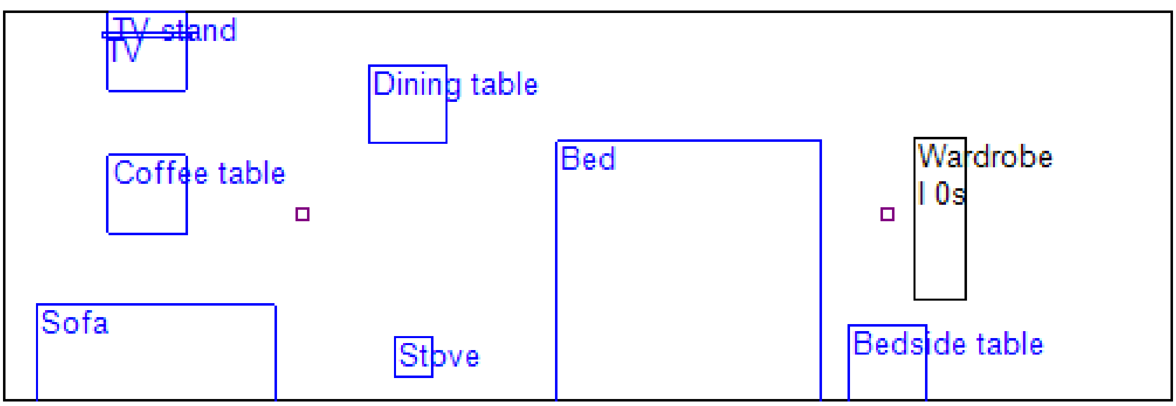


Figure 12.8: Floor plan for SME short stay apartment scenario, as displayed in B-RISK. Sprinkler locations are shown as small squares.

12.3.10.2 Long term leased apartment

In the case of a long term leased apartment, the location and quantity of contents were considered to be more uncertain. The fire load energy density (FLED) was estimated to have a mean of 500 MJ/m^2 and a standard deviation of 200 MJ/m^2, based on data reported in the New Zealand Fire Engineering Design Guide, 3rd edition[17] for a "home" occupancy. The FLED was assumed to be normally distributed with a lower bound of 50 MJ/m^2. The lower bound approximately corresponded to one bed and one table present in the room on an energy basis. The same items that were used for the short stay scenario were used. A maximum of two items were allowed for each of the item types with the exception of the bed which was only allowed one.

12.3.11 Item data

The item data listed here has been obtained from the literature for exemplar items where available it is for demonstration only and should not be used for other scenarios. The primary goal of these case studies is to demonstrate the ability of B-RISK to consider fire safety systems, not its ability to create realistic design fires.

Individual types of items and specific properties for individual items are listed in the section below. Properties common to several items are discussed in the following section.

It should be noted that when using lognormal distributions fit using @Risk for properties (eg. Hou[18]), the mean and standard distribution are the arithmetic mean and standard distribution values for the log normal distribution of the standard variable. The math libraries used by B-RISK use the normally distributed mean and standard deviation of the log transformed variable, which are the log transformed values of the geometric mean and standard deviation for the standard variable. This method of parameter entry is available in @Risk using the RiskLogNorm2 distribution.

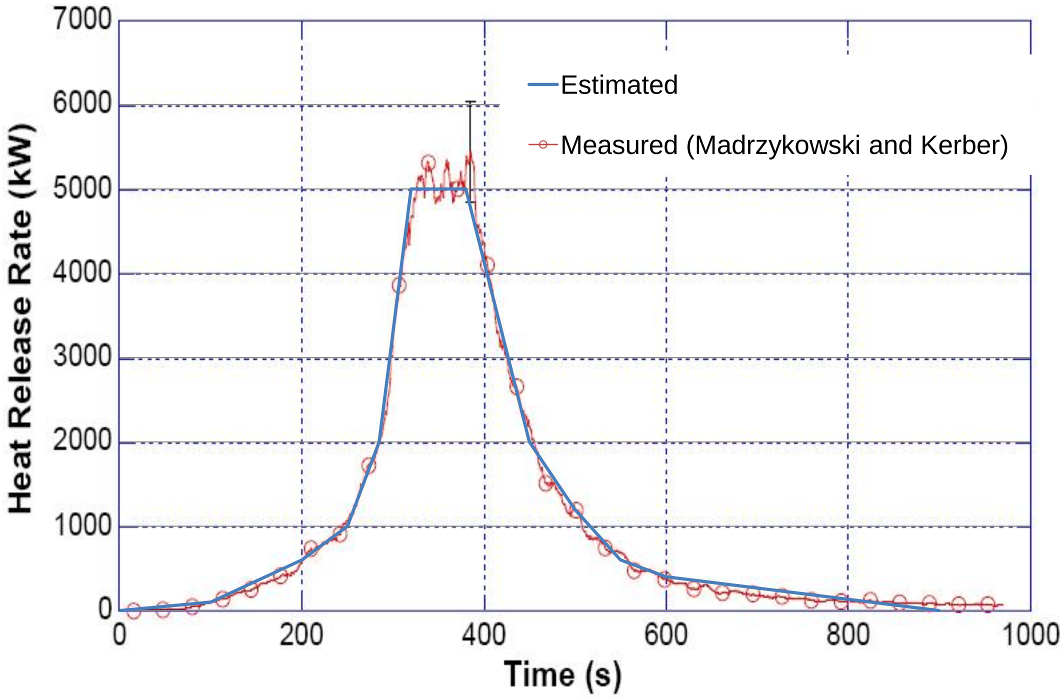


Figure 12.9: Estimated HRR for the bed, based on furniture calorimeter data from Madrzykowski and Kerber (shown)[20].

12.3.12 Item descriptions and specific material property estimates

12.3.12.1 Bed

The apartment was assumed to contain one king-sized bed. It has been noted that predicting the HRR of a bed is difficult due to interactions with the room geometry and ventilation conditions[19], thus there is a large source of uncertainty that is not accounted for with a single HRR curve for such an item. Nevertheless, a HRR history for the bed was estimated from a test performed at NIST, shown in Figure 12.9. The NIST test included a typical bed setup with a mattress, box spring, and bedding. The combustible mass was assumed to be 45 kg from the test data. The size of the bed was 2.03 m x 2.01 m x 0.42 m, which included both mattress and box springs.

CO_2 yield and h_c distributions were obtained from Hou's analysis[18] of the test data, using the total burn period. For the CO_2 yield, a lognormal distribution was used with μ = 0.81 and σ = 0.31 (as noted previously, this was the mean and standard deviation of the normally distributed logarithm of the CO_2 yield). For the h_c distribution, a normal distribution with μ = 21.5 MJ/kg and σ = 6.5 MJ/kg was

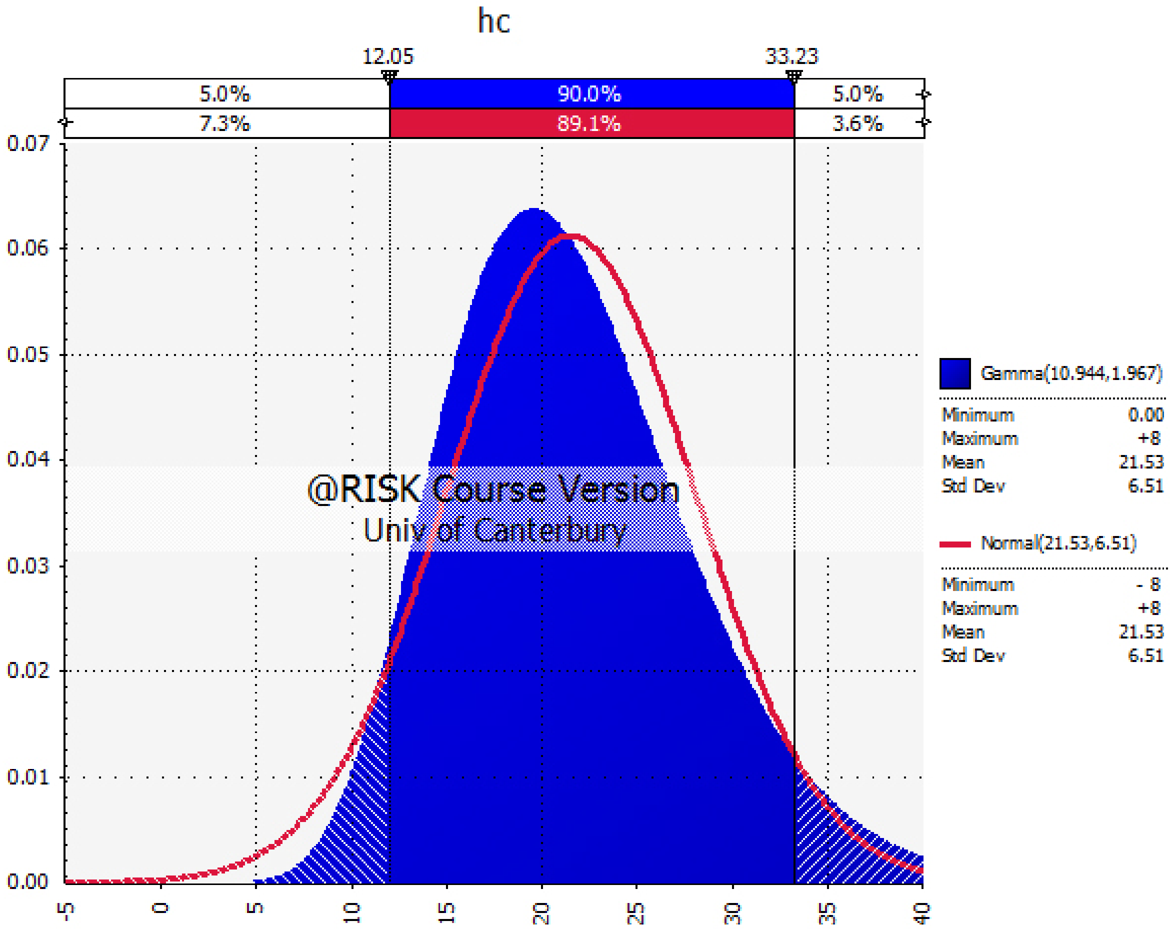


Figure 12.10: Normal distribution using sample mean and standard deviation compared with the gamma distribution proposed by Hou[18] for the king sized bed h_c.

used to approximate the gamma distribution proposed by Hou, since B-RISK did not include a gamma distribution option at the time. The two distributions can be seen in Figure 12.10. The HRRPUA was estimated to be 1220 kW/m^2 from the peak HRR divided by the plan area of the bed.

The ignition parameters for the PU/polyester combination and the soot yield for foam and fabric as described in Section 12.2 were used for the bed.

12.3.12.2 Wardrobe

The wardrobe was assumed to be constructed of 19 mm MDF. The estimated HRR was obtained from test 61 described by Lawson et al[21], shown in Figure 12.11.

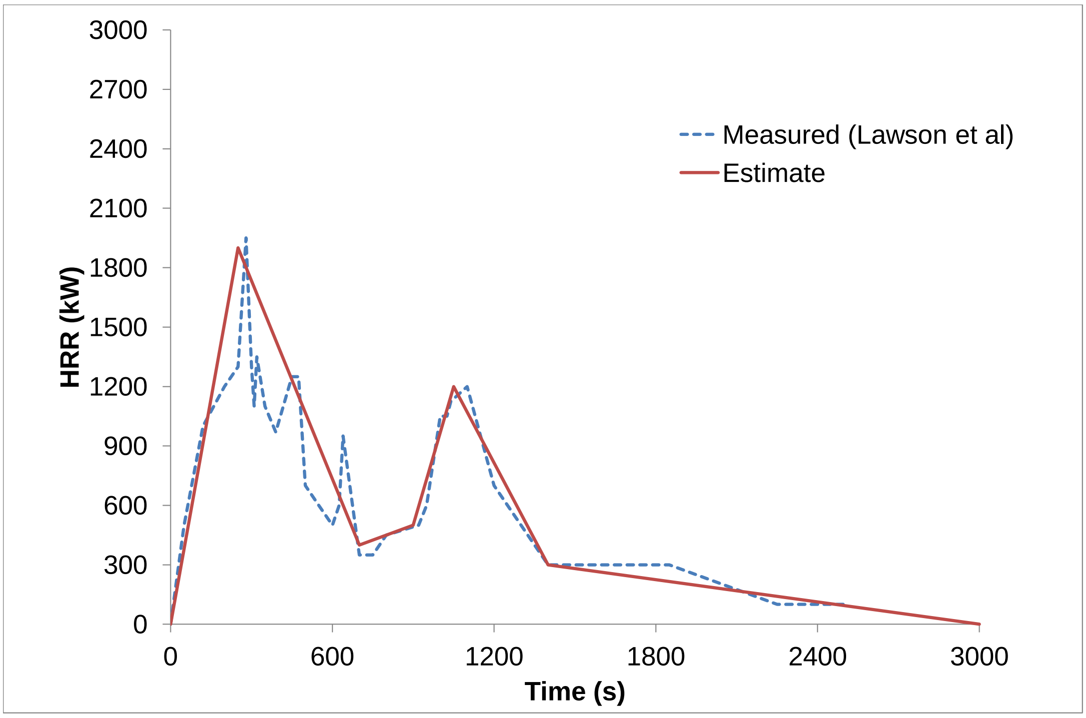


Figure 12.11: Estimated HRR for the wardrobe, based on furniture calorimeter data from Lawson et al (shown)[21].

The MDF yields, h_c, and ignition parameters described in Section 12.2 were used for the wardrobe. The combustible mass was estimated to be 120 kg, based on the NBS test. The dimensions of the wardrobe were 1.23 m x 0.4 m x 1.83 m.

12.3.12.3 Bedside, television, dining and coffee tables

The bedside, television, and coffee tables were approximated as .6 m x 0.6 m x 0.6 m medium density fibreboard (MDF) cubes, weighing 22 kg. The estimated HRR is shown in Figure 12.12.

A dining room set with three chairs and a table were included in the contents of the apartment. The chairs were assumed to provide a negligible contribution to the fire. The table was simulated as MDF construction, using the same parameters as used for the other tables.

The MDF yields, h_c, and ignition parameters described in Section 12.2 were used for the tables.

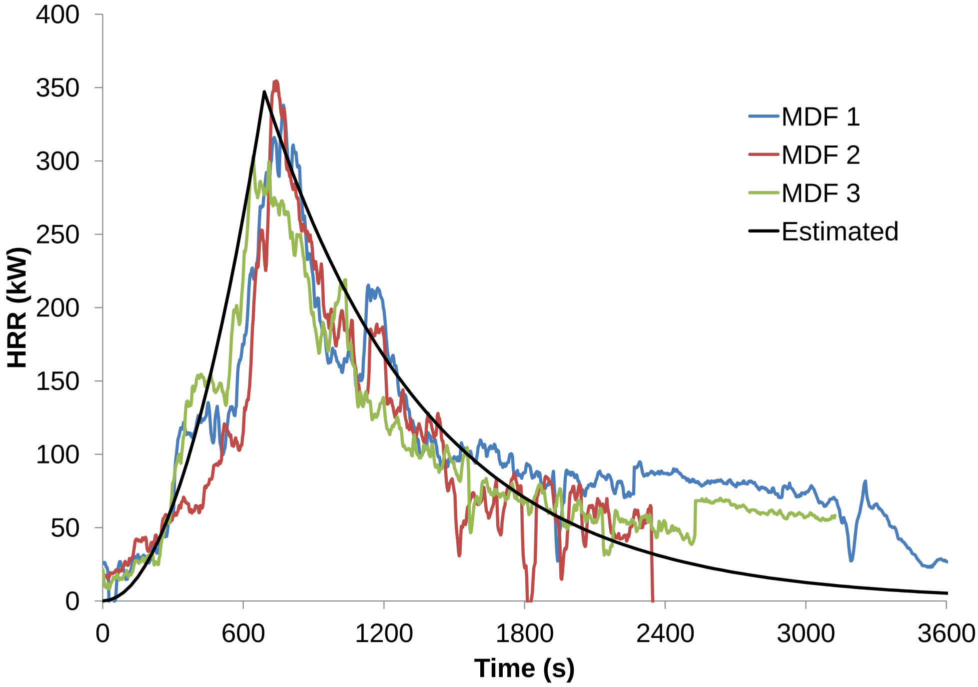


Figure 12.12: Estimated HRR for the bedside and coffee tables, based on furniture calorimeter data from MDF cubes (shown)[2].

12.3.12.4 Television

The television was estimated to have similar characteristics to the mock television tested for the B-RISK item-to-item validation tests[2]. The combustible mass was estimated at 3.72 kg. The ABS ignition properties from Section 12.2 were used for the television. The estimated HRR is shown in Figure 12.13.

For the yields and heat of combustion, plastics data from the SFPE handbook were used[5]. Specific data for ABS was not available for the CO_2 yield or radiant loss fraction so distributions were estimated from the data for other plastic materials. Table 12.4 lists the properties of ABS used. The HRRPUA was estimated to be 300 kW/m^2.

12.3.12.5 Sofa

The sofa was assumed to be a sleeper sofa similar to the one tested by Madrzykowski and Kerber[20]. The dimensions were 1.83 m x 0.75 m x 0.83 m, and the combustible

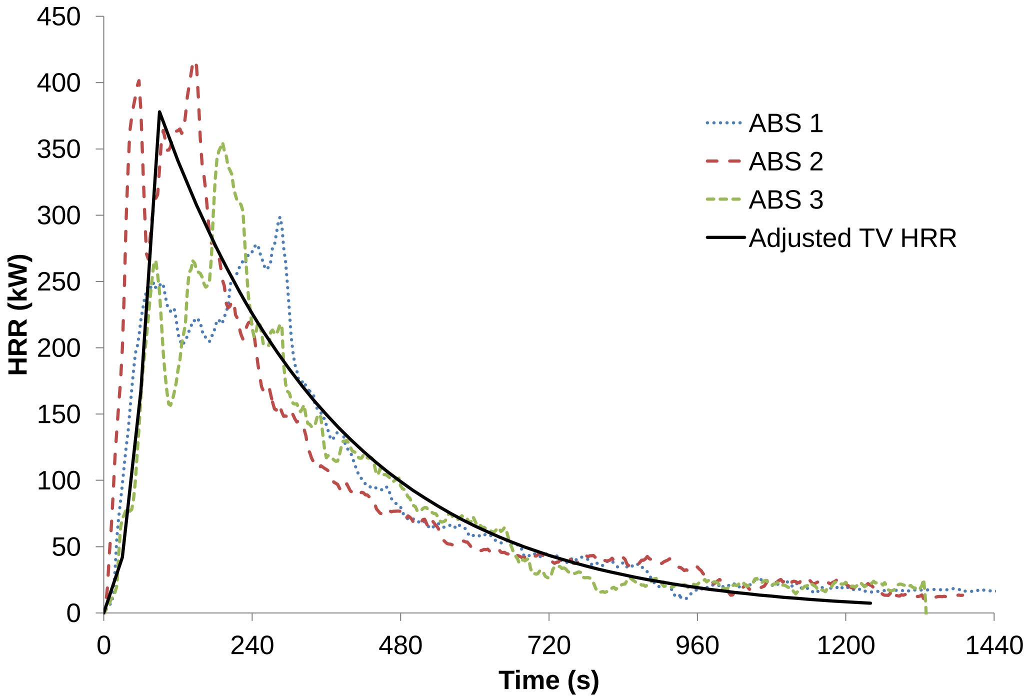


Figure 12.13: Estimated HRR for the television, based on furniture calorimeter data from a mock TV (shown)[2].

Parameter	Units	Mean	Standard Deviation	Lower bound	Upper bound
h_c	MJ/kg	30	2	26	34
Soot yield	kg/kg	0.105	0.002	0.085	0.12
CO_2 yield	kg/kg	2.33	0.15	2.3	2.36
χ_{rad}		0.5	0.1	0.3	0.7

Table 12.4: ABS properties estimated from SFPE handbook data[5].

mass was assumed to be 48 kg. The HRR measured by Madrzykowski and Kerber and the estimated HRR are shown in Figure 12.14.

The ignition parameters for the PU/polyester combination and the soot yield for foam and fabric as described in Section 12.2 were used for the sofa. The HRRPUA was estimated to be 1800 kW/m^2.

CO_2 yield and h_c distributions were obtained from Hou's analysis[18] of the test data, using the total burn period. For the CO_2 yield, a lognormal distribution was used with μ = 0.7 and σ = 0.17. For the h_c distribution, a normal distribution with μ = 16.9 MJ/kg and σ = 2.8 MJ/kg was used to approximate the gamma distribution proposed by Hou.

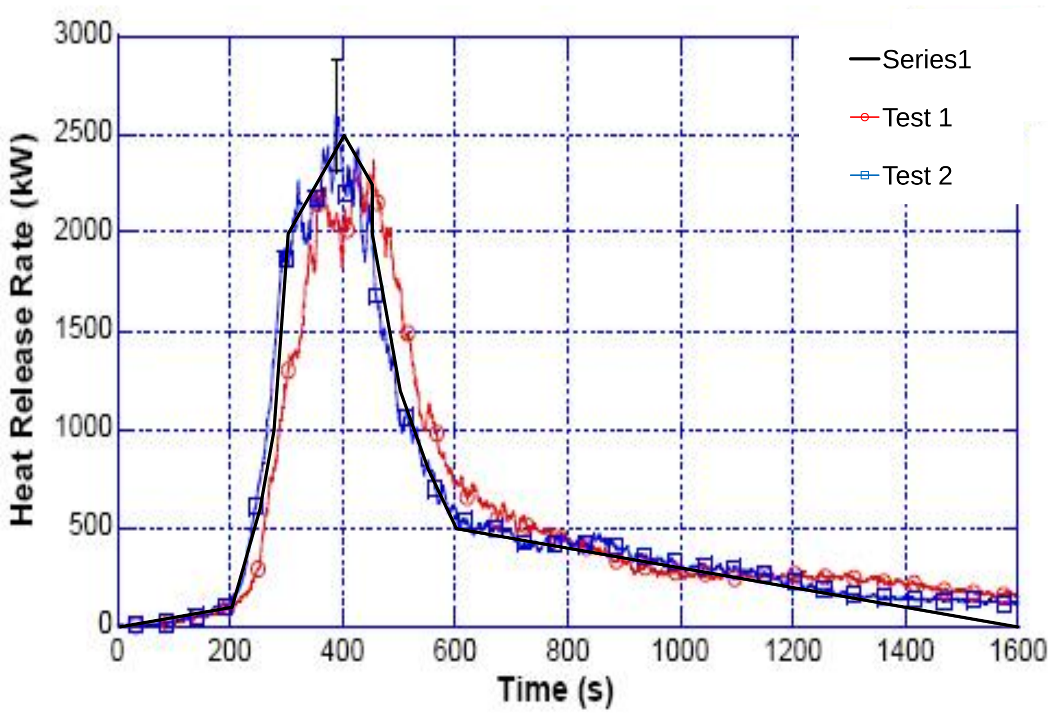


Figure 12.14: Estimated HRR for the sofa, based on furniture calorimeter data from Madrzykowski and Kerber (shown)[20].

12.3.12.6 Stove

While stoves are generally non-combustible, stove top fires are common. An item corresponding to a 30 cm diameter pan with 0.5 kg oil was added at stove top height (1 m). It was assumed that if the pan was not the first item ignited that it would not contribute to the room HRR, because it is not likely that an occupant would keep a pan of oil on the stove any time they were not cooking with it. To prevent ignition by other items, the FTP parameters were set high. The oil was approximated as light hydrocarbon oil, with heat of combustion, species yield, and radiant loss fraction data from the SFPE handbook[5]. The HRR was estimated to be constant at 30 kW for 140 s, based on the pool area in the pan and the estimated energy content of the assumed volume of oil.

12.3.12.7 Properties used for t^2 design fire

The properties of the sofa for the item-to-item were used with the α distribution from Young[22] (discussed in Chapter 5) for the t^2 design fire scenario.

12.3.13 Modelled compartments

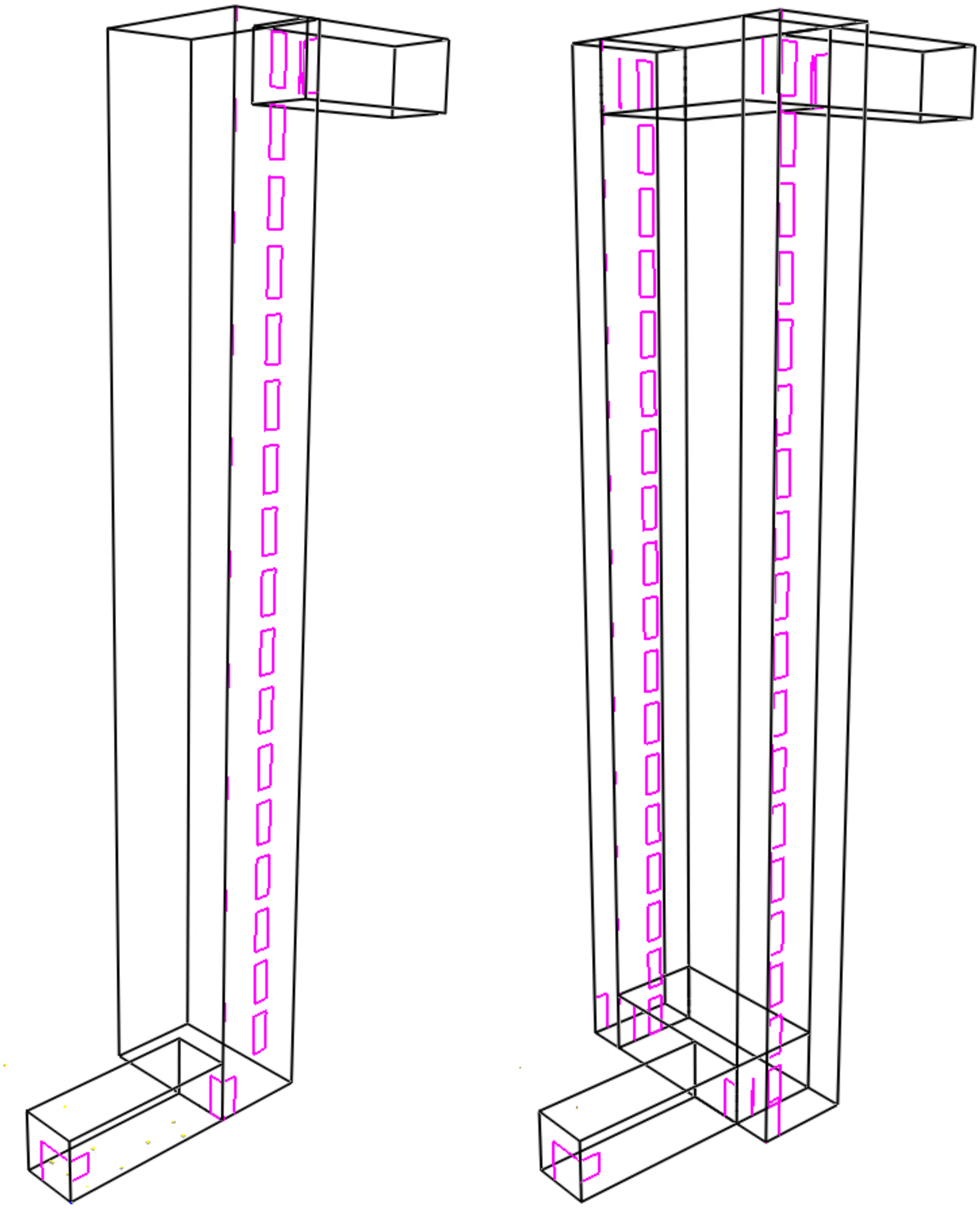
The modelled compartments for the alternative and compliant buildings are shown in Figure 12.15. The modelled compartments included the apartment of fire origin and one remote apartment on the top floor to determine smoke spread into other apartments. The apartment dimensions were 9 m x 3 m x 3 m high. For the alternative building, a single vertical compartment was used to model the stairwell/landing compartment. The model geometry for the alternative building was similar to that used by one of the experts for the determination[23]. The alternative stairwell was modelled as a shaft 7.5 m x 4.7 m x 48 m tall. For the compliant building, the two separate stairwells were included, as well as the horizontal lobby areas connecting the apartment of fire origin and the remote apartment to the stairwells. The stairwells were modelled as 48 m tall shafts with plan dimensions of 4.7 m x 2 m. The lobby dimensions were 9 m x 4.7 m x 3 m high. The B-RISK default boundary material (concrete) and thickness (100 mm) were used.

12.3.14 B-RISK results

Due to time and computational resource constraints, 500 iterations were completed for each of the four B-RISK configurations; the alternative building with t^2, short stay, and long term apartment design fires, and the compliant building with the t^2 design fire.

12.3.14.1 Comparison between design fire scenarios

The t^2, short stay, and long term design fire scenarios produced similar maximum HRR distributions for the alternative building, as shown in Figure 12.16. This was due primarily to the sprinklers limiting the maximum HRR for the majority of the fires in all design fire scenarios, keeping the maximum HRR below 1 MW. There was more uncertainty in the time to sprinkler activation for the t^2 design fire option as shown in Figure 12.17, due to the greater uncertainty in the t^2 growth rate distribution. If the sprinklers failed to have an effect on the fire the maximum HRR increased beyond 1 MW in some circumstances, depending on the fire growth rate or how many items ignited for the t^2 and item-to-item fire spread scenarios, respectively,



(a) Alternative (b) Compliant

Figure 12.15: The B-RISK models for the SME building as seen in Smokeview.

and the total amount of available ventilation determined by the size and number of open vents. Fires up to approximately 20 MW were simulated in some instances. These larger fires tended to lead to shorter times to untenability, as expected. Large fires such as these may begin to adversely affect the compartmentalisation of the building. This analysis did not include the effects of the fire on the passive building elements, so additional investigation of these scenarios perhaps using alternative

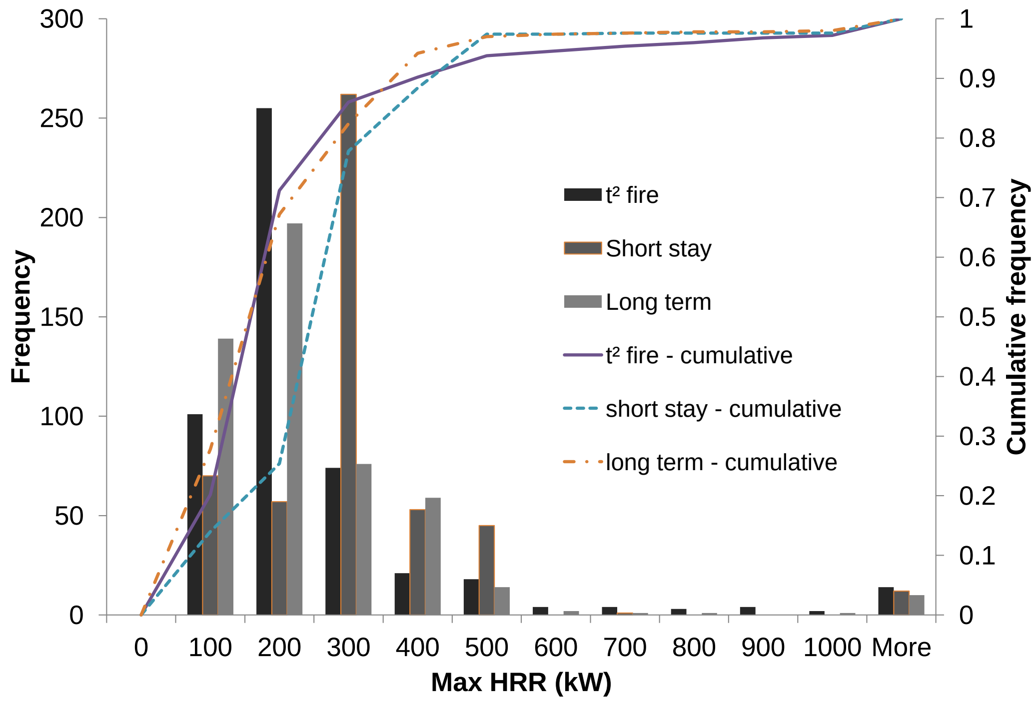


Figure 12.16: Maximum HRR histogram comparing design fire scenarios for the SME alternative building.

models would be required in a full risk analysis.

The fire did not spread beyond the first item in the majority of the iterations for the two item-to-item design fire generator scenarios, as shown in Figure 12.18. Approximately 18% of the iterations for the short stay scenario had fire spread to one item, which was primarily due to the fact that the TV was placed directly above the TV stand. There was item-to-item fire spread in approximately 2% of the long term stay scenario, including one iteration where four items were ignited. As the random item placement algorithm does not place items over top of each other (as was the case for the TV on the TV stand in the short stay scenario), the minimum distance was larger for the long term scenario. The presence of the sprinklers also prevented item-to-item fire spread. The use of piloted ignition FTP properties for the item-to-item fire spread input may have increased the number of subsequent items ignited.

Less than 1% of simulations exceeded the FED criteria for each type of design fire, both for toxic gases and for thermal radiation, even in the fire compartment. For the alternative building, neither FED criteria was exceeded in any iterations for

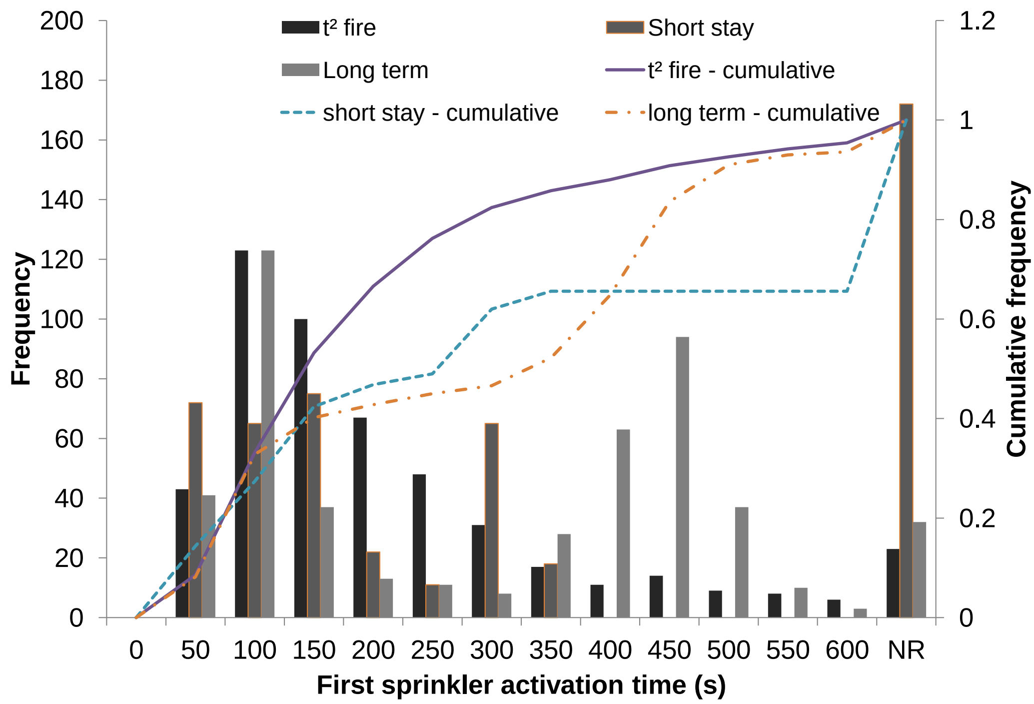


Figure 12.17: Sprinkler activation time histogram comparing design fire scenarios for the SME alternative building. NR = no sprinkler response in the simulated time.

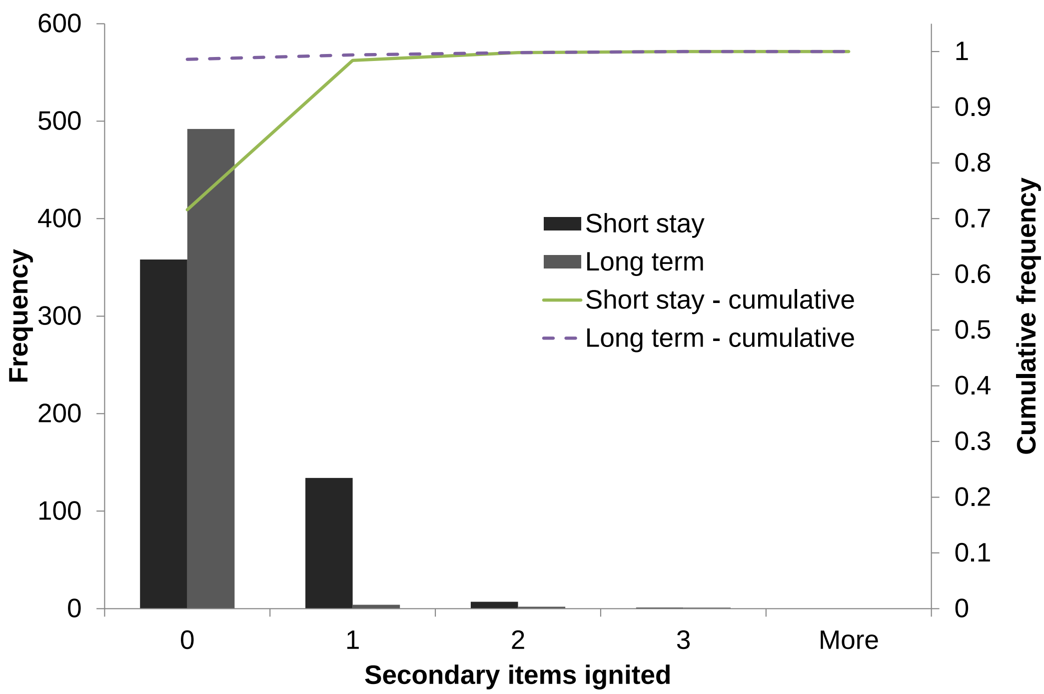


Figure 12.18: Secondary item ignition for the SME alternative building design fire scenarios.

the stairwell and remote apartment. Figure 12.19 compares the number of iterations for each type of design fire where the FED_g was reached in the fire compartment.

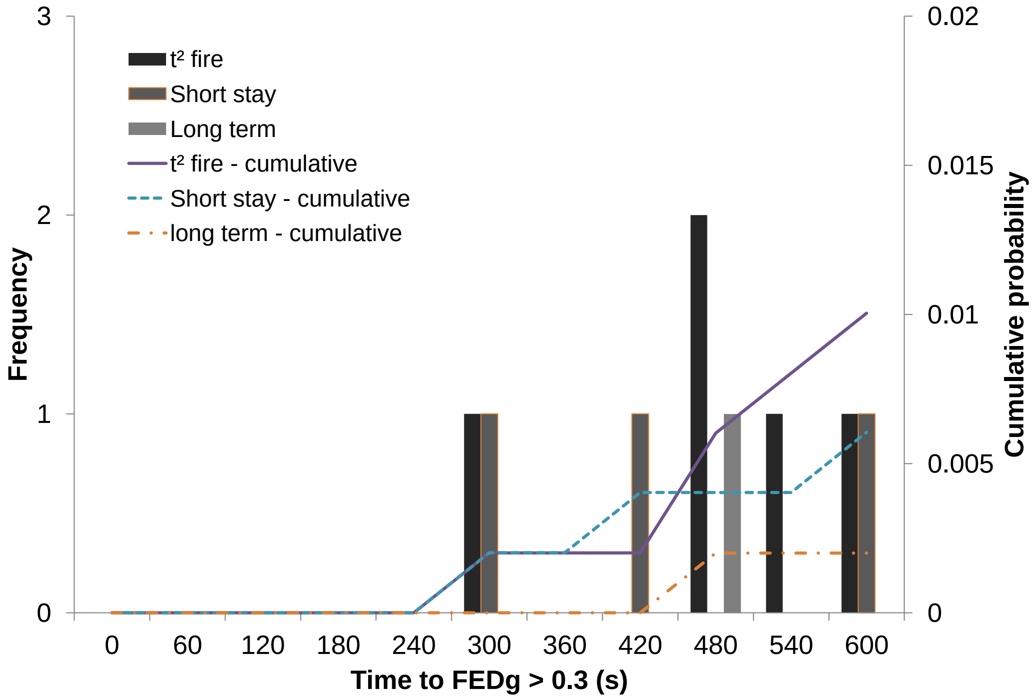
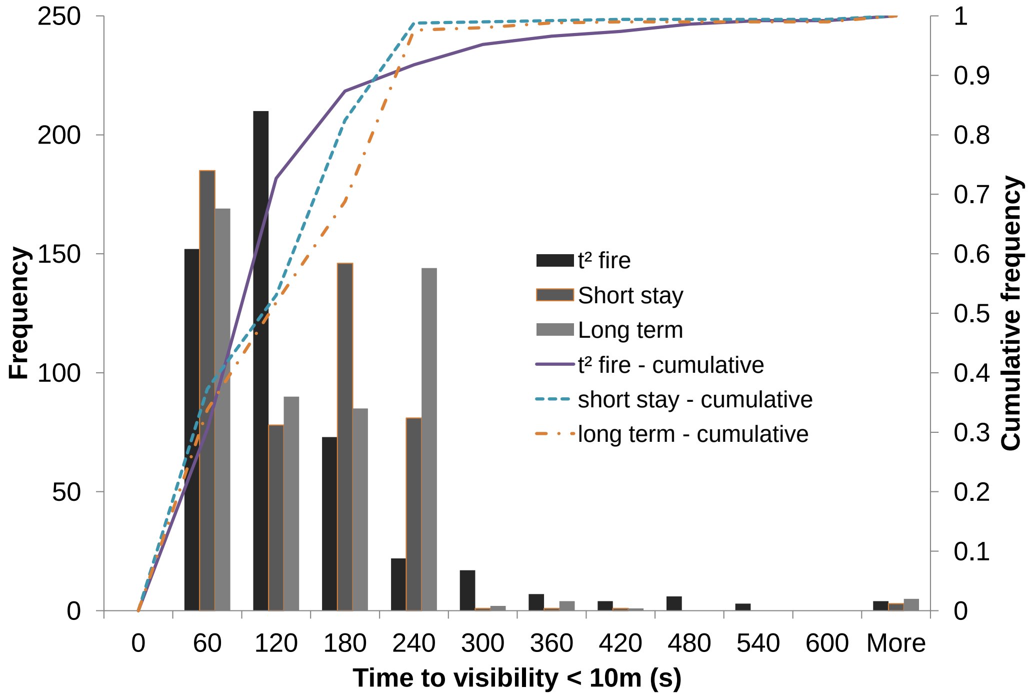


Figure 12.19: Histogram of runs reaching the FEDg criteria in the fire compartment for the SME alternative building design fire scenarios.

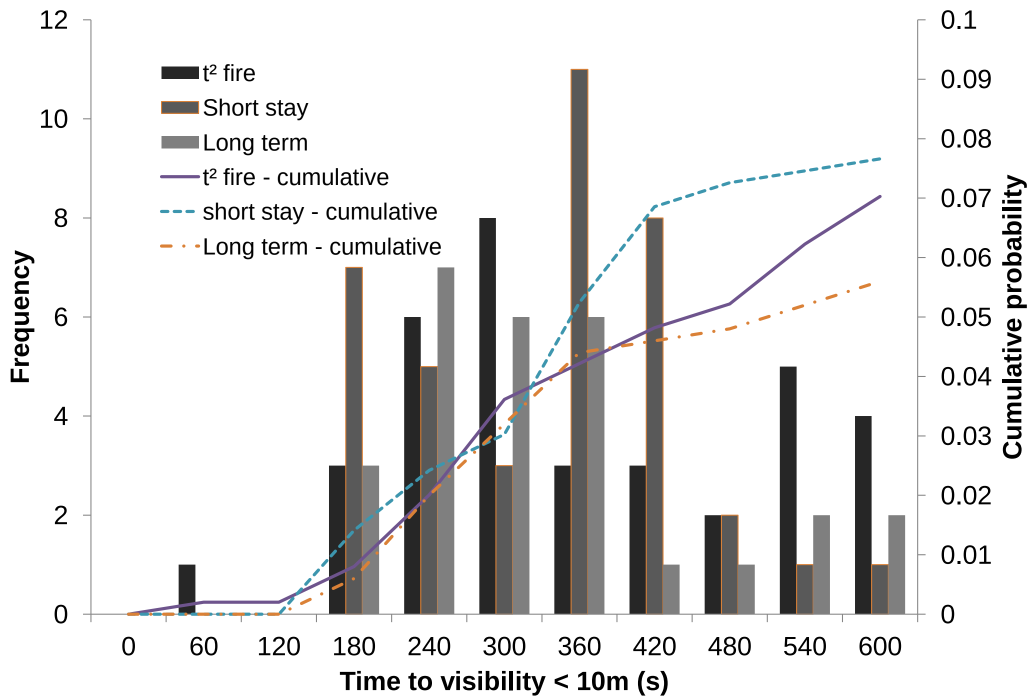
More iterations exceeded the visibility criteria with the t^2 design fire scenario. The histogram of times where the visibility was exceeded in the alternative building are shown in Figure 12.20.

The visibility criteria was exceeded in the stairwell during the simulated time of 600 s for 35 iterations with the t^2 design fire, compared to 38 and 23 for the short stay and long term stay scenarios, respectively.

There did not appear to be any advantage to using the item-to-item DFG to generate the design fire relative to using the t^2 design fire, so the t^2 design fire was used for the comparison between the compliant and alternative buildings as it was more computationally efficient to run.



(a) Fire compartment



(b) Stairwell

Figure 12.20: Visibility criteria histograms for the fire compartment and stairwell in the SME alternative building.

12.3.14.2 Comparison between the SME compliant and alternative buildings using the t² design fire scenario

A comparison of the maximum HRR between the SME compliant and alternative buildings is shown in Figure 12.21. The maximum HRR for the compliant building tended to be higher than the alternative building, due to the slower responding standard response sprinklers in the compliant building. The response time of the first sprinkler is shown in Figure 12.22.

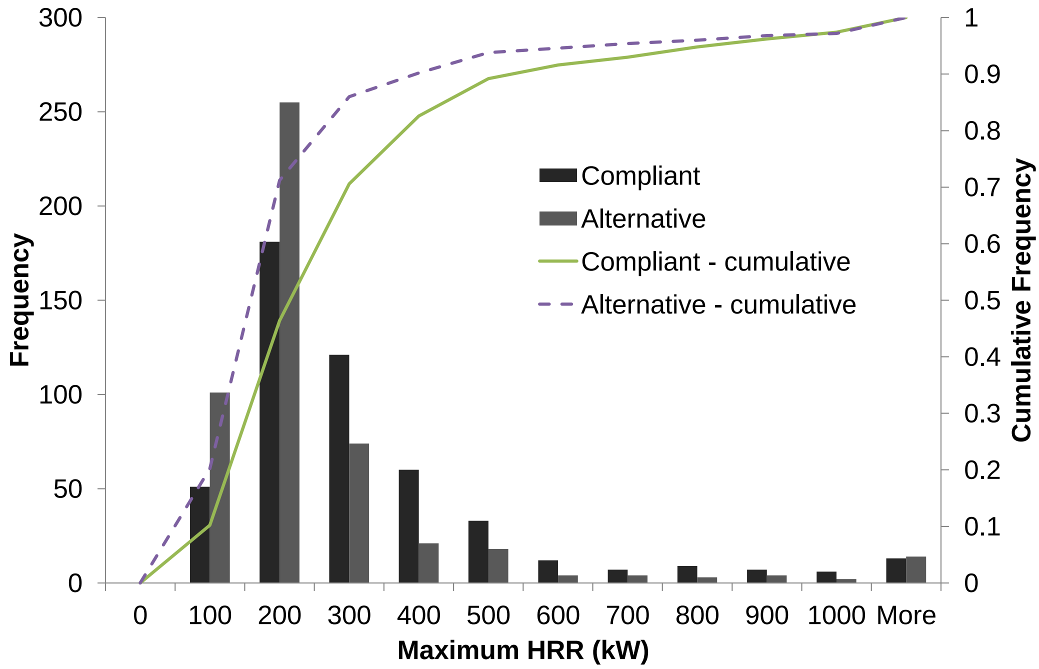


Figure 12.21: Maximum HRR histogram comparing the SME alternative and compliant buildings using the t^2 design fire scenario.

The FED criteria was not exceeded for either the compliant or the alternative buildings for any of the compartments outside of the fire compartment so only visibility was used for comparison. Figure 12.23 compares the number of runs for the compliant and alternative buildings where the visibility criteria was exceeded in the stairs.

Compared to the individual stairwells in the compliant building, the probability of exceeding the visibility criteria in the alternative building stairwell within the simulated time was nearly double. When compared to runs where the visibility criteria in both stairwells in the compliant building was reached (ie. when occupants

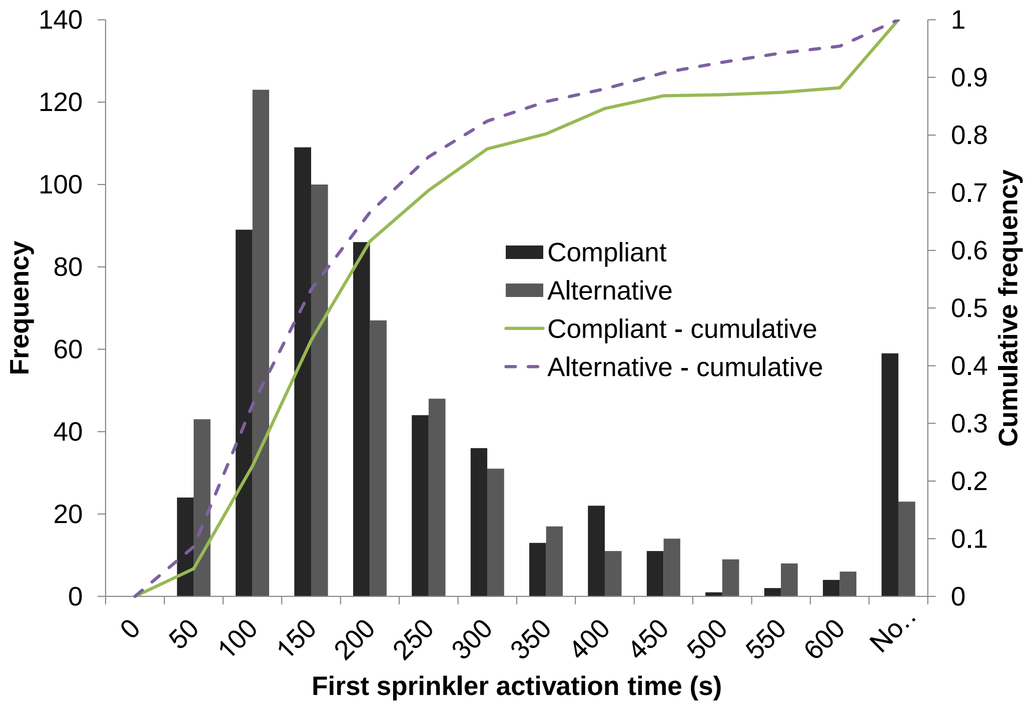


Figure 12.22: Sprinkler activation time histogram comparing the SME alternative and compliant buildings using the t^2 design fire scenario.

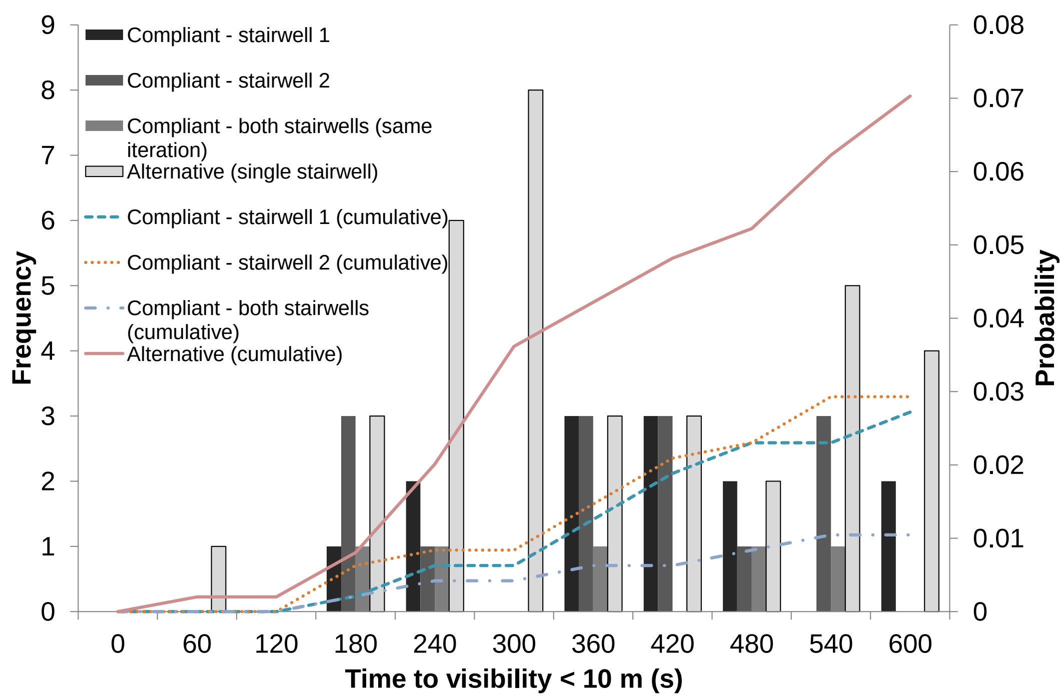


Figure 12.23: Visibility criteria histogram comparing stairwell visibility in the SME alternative and compliant buildings using the t^2 design fire scenario.

in upper floors had no tenable escape route option), the visibility in the alternative stairwell reached the criteria almost seven times more often.

A comparison between the time to reaching the visibility criteria for the fire floor lobby in the compliant building and the stairwell in the alternative building was done as a measure of the risk to the occupants in other apartments on the fire floor, shown in Figure 12.24. Approximately 70% of the iterations reached the visibility criteria in the compliant building fire floor lobby, compared to the 8% of iterations where the visibility criteria was reached in the alternative building stairwell.

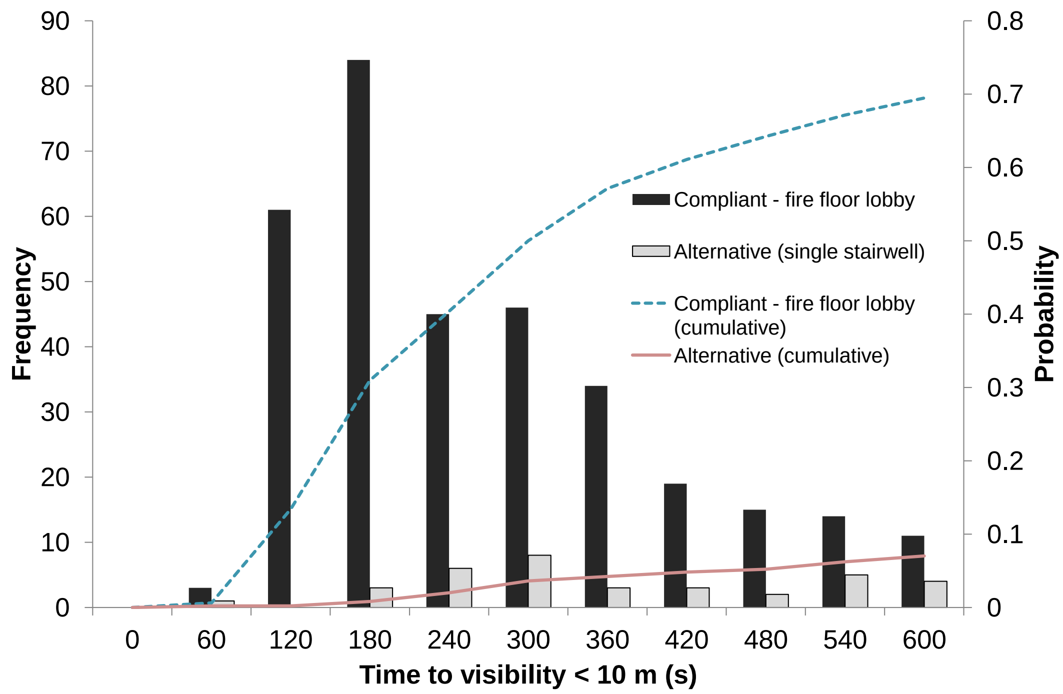


Figure 12.24: Visibility criteria histogram comparing the SME alternative building stairwell and the compliant building fire floor lobby using the t^2 design fire scenario.

The visibility criteria in the remote apartment was never reached in the compliant building. It was reached in 1.4% of the runs in the alternative building.

12.3.14.3 Effect of stairwell pressurisation

The addition of stairwell pressurisation in the simulated compliant building did not measurably reduce the estimated probability that both stairwells would become untenable simultaneously, as shown in Figure 12.25, although the probability was only

1% both with and without pressurisation. In order to reach untenability in both stairs, a combination of a failed sprinkler system, doors open to both stairwells, failed pressurisation in both stairwells, and a sufficient fire growth rate to cause untenability within the simulated time had to occur within the same simulation. This made the outcome sensitive to the random selection of input variables for individual runs. As expected the probability of individual stairwells becoming untenable within the simulated time was higher, reaching 7% where pressurisation was not present and 5% where pressurisation was present, shown in Figure 12.26. The low probability of both stairwells becoming untenable with or without pressurisation indicates that pressurisation would have a greater effect on fire risk in the alternative building compared to the compliant building. The compliant building without stairwell pressurisation was still safer than the alternative building for occupants above the fire floor, when comparing tenability in the means of escape during the simulated time.

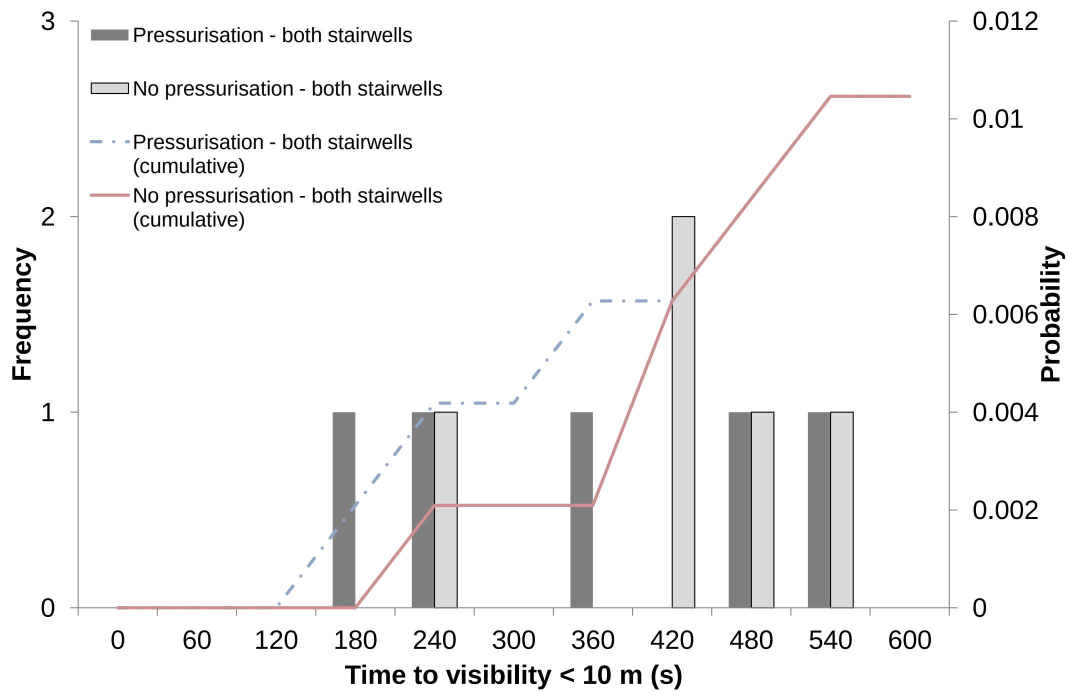


Figure 12.25: Visibility criteria histogram comparing the probability of both stairwells becoming untenable in the SME compliant building with and without stairwell pressurisation, using the t^2 design fire scenario.

Based on the ASET analysis described here, it appears that the alternative building may not as safe as the compliant building for occupants above the fire

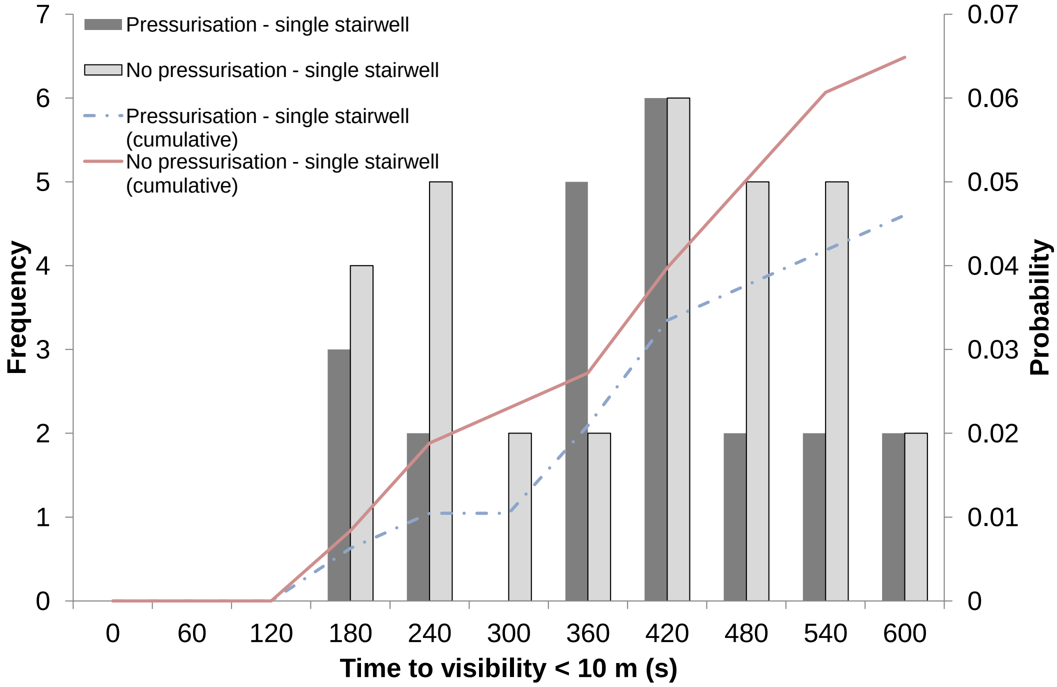


Figure 12.26: Visibility criteria histogram comparing the probability of a single stairwell becoming untenable in the SME compliant building with and without stairwell pressurisation, using the t^2 design fire scenario.

floor, although the compliant building may have more risk for occupants on the fire floor. This does not take different evacuation schemes into consideration, and does not evaluate if the alternative building is "safe enough" to meet society's objectives.

12.4 140 William Street

The second building where risk is compared using B-RISK is the 140 William Street building described in Chapter 1. An elevation view of the building can be seen in Figure 12.27. A typical plan view of a floor in the building is shown in Figure 12.28. Similar to the original risk assessment, three building design configurations were compared with B-RISK; "existing", "deemed-to-satisfy" (DTS, comparable to the Building Code of Australia (BCA) configuration in the original report), and "refurbished".

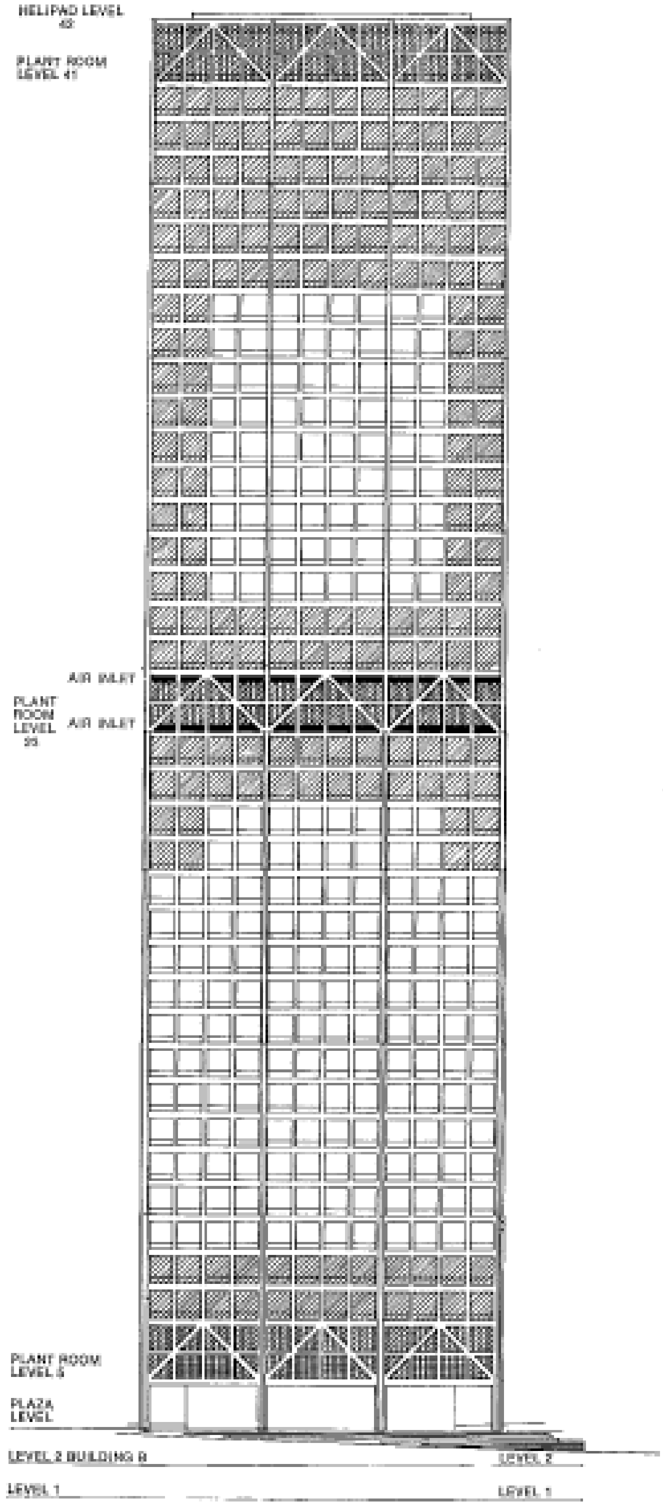


Figure 12.27: 140 William Street building elevation view, from Thomas et al[24].

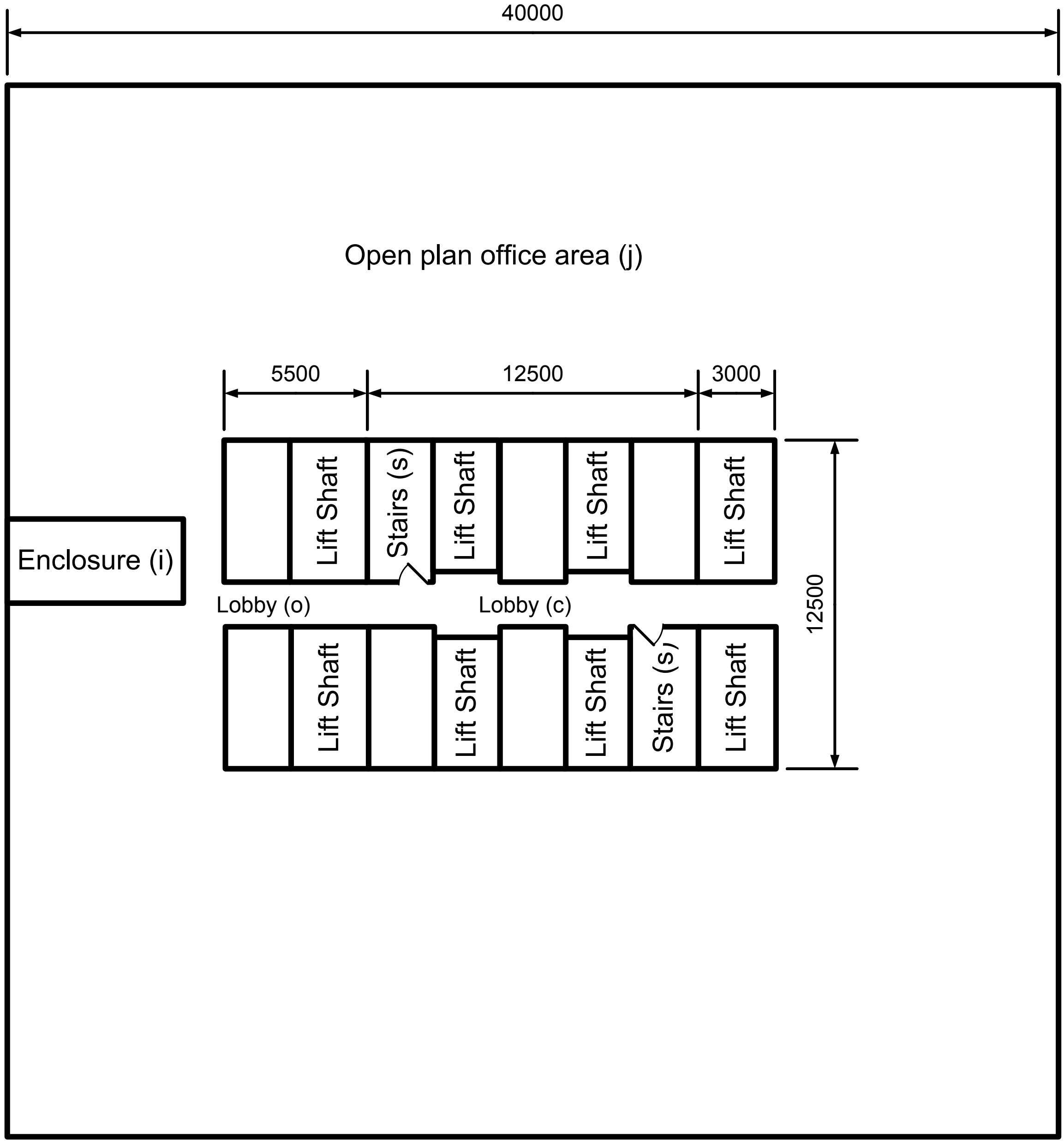


Figure 12.28: 140 William Street building typical plan view, from Thomas et al[24]. Dimensions in mm.

12.4.1 Modelled compartments

In the original report, the fire was assumed to initiate in a small room on one level. The fire model represented the building space in simplified enclosures as follows:

1. Compartment of fire origin (i)

2. Remainder of office space on fire floor (j)
3. Outer lobby (o)
4. Inner lobby (c)
5. Stairwell (s)
6. Floor above fire (k).

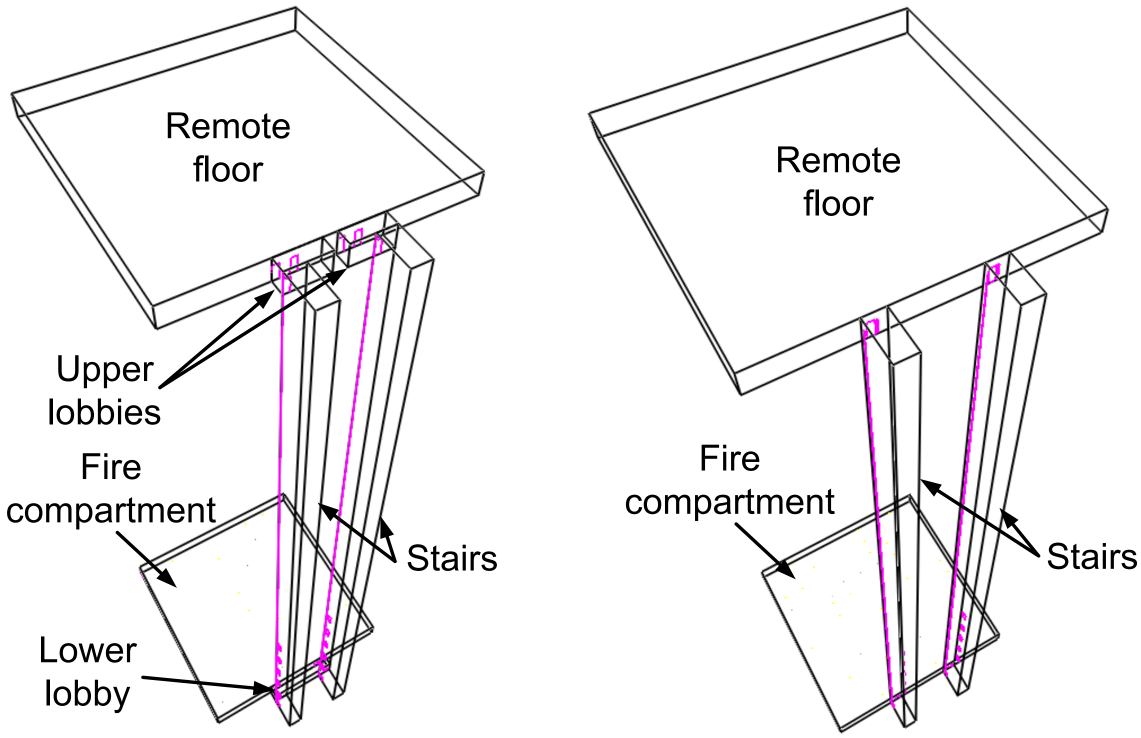
In the B-RISK model, the fire was assumed to start in the compartment j which represented the open space on the fire floor, and the entire office area on the floor was assumed to be open plan. This decision was made to demonstrate the full sprinkler system hydraulic modelling capabilities. For actual building design, it would be necessary to consider fires in both compartment i and j. Since B-RISK is not capable of directly modelling the exact floor geometry with the lobbies and lift shafts located in the centre of the office floor, the lobbies and stair shafts were modelled adjacent to the office area as shown in Figure 12.29. For the existing and refurbished building, a single combined lobby was modelled on the fire floor and split lobbies were modelled on the remote floor. For the DTS building, the office areas were connected directly to the stair shafts without lobbies.

12.4.2 Building fire protection features in the B-RISK model

In general, each occupied floor in all three configurations consisted of a mixture of open-plan office area and a number of small office enclosures surrounding a central services corridor, which included two protected stairwells and eight lift shafts. The following sections summarise how each aspect of the building's fire protection systems relevant to the scope of this thesis were considered in the risk analysis. For more detailed information including diagrams, refer to the original report[24].

12.4.2.1 Structural member fire protection

As noted, one of the major changes proposed for the refurbishment was to remove the asbestos-based fire protection material from the floor slab and associated beams.



(a) Existing and refurbished (b) DTS

Figure 12.29: The B-RISK models for the 140 William Street building as seen in Smokeview.

A set of fire tests were conducted to determine the performance of the unprotected structural elements, and it was concluded that they would perform adequately under the required fire conditions. While the major objective of the original study was to determine if fire protection was required on these elements, it is not considered here because structural fire protection is not part of the scope of the B-RISK project.

As specific information was not available from the original risk analysis, the curtain walls of the compartment of fire origin and the floor above the fire were assumed to be 20 mm plate glass and the walls of the remaining compartments were assumed to be 100 mm concrete for heat transfer purposes. The floors and ceilings of all of the compartments were assumed to be 100 mm concrete. Standard B-RISK database properties were used for both types of materials. Similar leakage distributions were used as were previously used for the SME building designs.

12.4.2.2 Fire doors

In all of the buildings, the stairwell access doors are fire-rated and have automatic closers. For the existing building, a small lobby for each stairwell is also separated from the outer lobby area by fire-rated doors. The DTS building did not require the secondary doors since a zone or sandwich pressurisation system was included (the DTS solution required either secondary doors or the zone pressurisation system). For the proposed building, the secondary fire doors were included but were held open and automatically closed in the event that either or both of the two smoke detectors positioned outside each door activated.

For doors with closers and no hold open devices, the probability that the door was held open was estimated based on the office data discussed in Chapter 8 from the 1970 UK study[13]. A normal distribution with a mean reliability of 0.82 and a standard deviation of 0.0045 was estimated from a binomial distribution with n = 8055 and p = 0.82. Hold open devices for doors equipped with them in the refurbished building were activated by the smoke detection system, and were assumed to have a reliability of 1.

Similar door leakage distributions were used as were previously used for the SME building designs, discussed in Section 12.3.7.

12.4.2.3 Sprinkler System

Since the water supply flow characteristics present at the building site were not readily available, a supply flow characteristic at the most remote floor was assumed as shown in Figure 12.30. The water supply was chosen to meet the OH hydraulic requirements for the DTS building with reasonable pipe sizing but without excess supply to ensure the system was challenged. The shape of the curve was chosen to allow higher spray densities with less sprinklers activated, and to ensure the critical minimum pressure threshold was reached if more than six sprinklers were activated.

All of the sprinklers on the fire floor were modelled along with the hydraulic system. The sprinkler thermal response parameters for the 140 William Street building B-RISK model were the same as described in Table 12.3 for the SME building

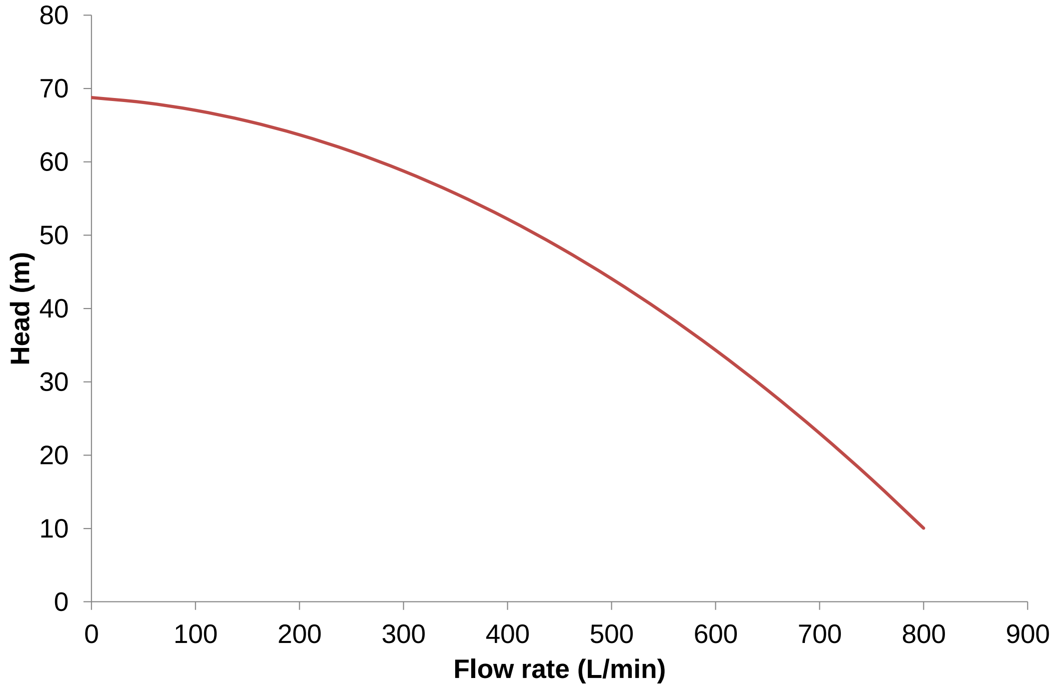


Figure 12.30: Hypothetical water supply for the 140 William Street building, measured at the riser on the most hydraulically remote floor.

standard response sprinklers. The piping was specified to meet the hydraulic requirements for ELH and OH1 hazard classifications for commercial buildings. For the ELH classification, the six most hydraulically remote sprinklers were required to be supplied with a minimum spray density of 4.1 mm/min or a minimum pressure of 50 kPa, with a maximum spacing of 4.6 m and single sprinkler coverage area of 21 m^2. For the OH1 system, the six most hydraulically remote sprinklers were required to be supplied with a minimum spray density of 5.5 mm/min or a minimum pressure of 50 kPa, with a maximum spacing of 4 m and a maximum coverage area of 12 m^2 per sprinkler. These criteria were based on the NZS 4541:2007, which were slightly different than the original Australian requirements for the OH hazard classification which had a maximum spacing of 3.5 m. Sprinkler K factors of 8 $\frac{L/min}{\sqrt{kPa}}$ were used, with 50 mm and 38 mm piping as shown in shown in Figures 12.31 and 12.32 for the ELH and OH1 configurations, respectively. Due to the limitations of the B-RISK compartment geometry, the exact sprinkler configuration that would be present in the room was not specified, but was matched to the modified compartment geometry used in B-RISK.

The fire HRR was set to resume growing if the sprinkler system was "overrun";

that is, if the critical minimum supply pressure or spray density was reached. This resulted in all of the sprinklers activating if the system was overrun.

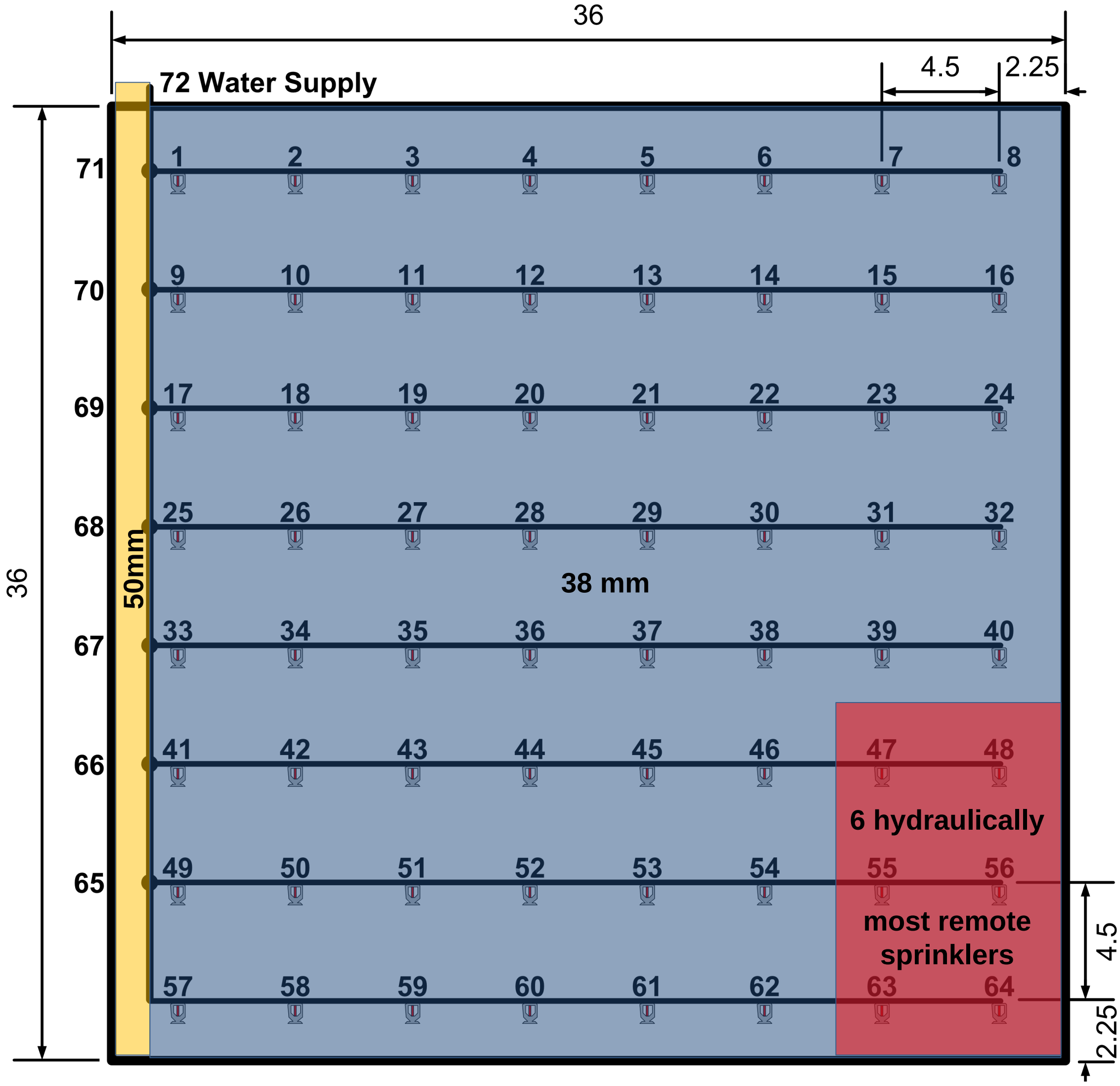


Figure 12.31: ELH sprinkler layout for one floor of the 140 William Street building. Nodes used for the hydraulic model are shown. Dimensions shown in m, except for nominal pipe diameters shown in mm.

As no data has been found to support the influence of monitored valves on sprinkler system effectiveness, they were not taken into consideration. The distributions from Chapter 4 for sprinkler reliability and efficacy were used for the existing and refurbished buildings, while the distributions used for the SME alternative

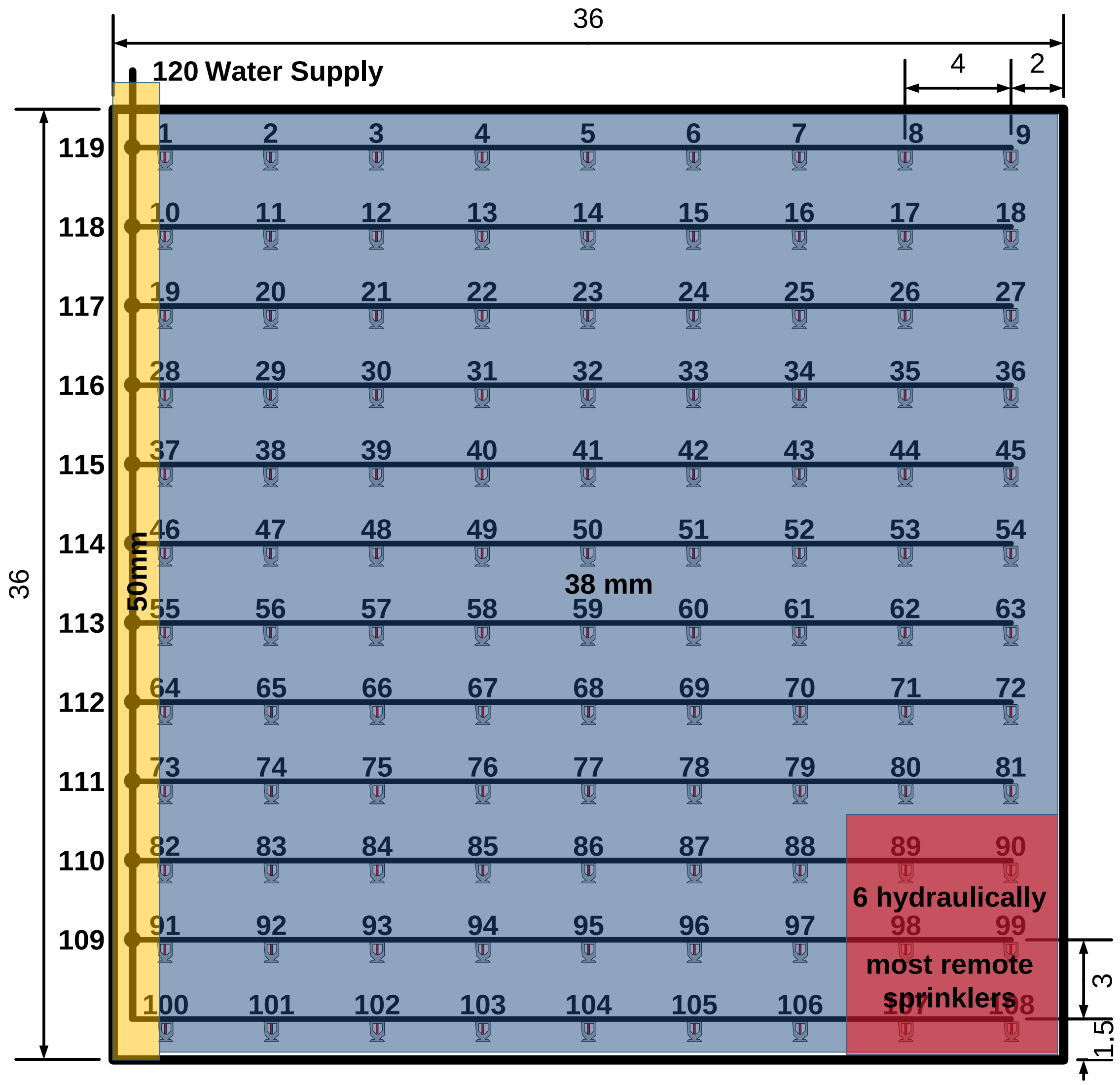


Figure 12.32: OH sprinkler layout for one floor of the 140 William Street building. Nodes used for the hydraulic model are shown. Dimensions shown in m, except for nominal pipe diameters shown in mm.

building were used for the refurbished building due to the additional gravity water supply.

12.4.2.4 Smoke Management System

In the existing building, neither stairwell pressurisation or zone smoke control was available in case of fire. However, the air handling system would shut down if a smoke detector activated or the sprinkler pressure switch indicated a low pressure. For the DTS and refurbished building, both stairwell pressurisation and zone smoke control were included, activated by the same means as the air handling shut down in the existing building.

The DTS and refurbished design included more smoke detectors than the existing building, which only had smoke detectors installed in the return air ducts.

Only the stairwell pressurisation system was included in the B-RISK model, not the zone smoke control system. Smoke detectors were placed in the stairwells to activate the fans and in the fire compartment to activate the doors with hold-open devices for the refurbished building. The hold-open device reliability was set at 1. The inputs for the pressurisation system were consistent with the SME building as described in Section 12.3.8.

12.4.3 Design fires

The design fire was located in the open plan office area. Two design fire configurations were considered: a t^2 fire using the distribution from Young for α and a randomly populated item-to-item design fire generator configuration using workstations as the items. For the t^2 fire, the peak HRR was set at a constant 20 MW as per C/VM2[25], which was reached if the growth rate was sufficient and the sprinklers did not intervene due to the available air in the fire compartment. The FLED for the office floor was estimated to have a mean of 800 MJ/m^2 with a standard deviation of 300 MJ/m^2, based on reported data for an "office, business" occupancy[17]. The FLED was assumed to be normally distributed with a lower bound of 100 MJ/m^2, to prevent an empty floor (FLED = 0 MJ/m^2) or a negative FLED. The 100 MJ/m^2 lower FLED bound corresponded to a minimum of 64 workstations in the fire compartment. The soot yield for both configurations was set to a uniform distribution from 0.05 kg/kg to 0.2 kg/kg based on the range discussed in BRANZ Study Report Number 185, which was used as the basis for the C/VM2 soot yield criteria[4].

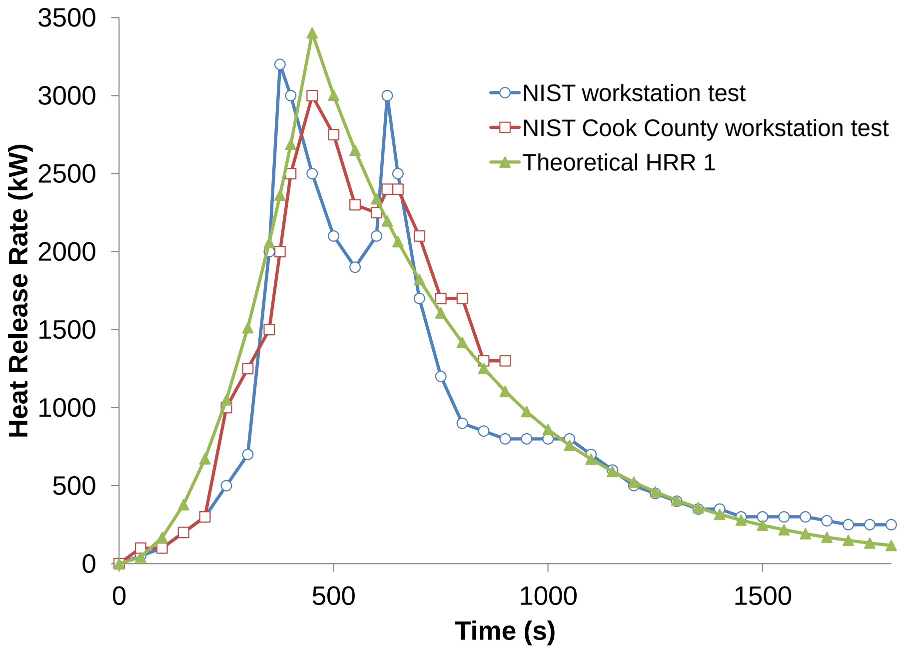


Figure 12.33: Heat release rate from two NIST workstation tests[26,27] and the theoretical HRR used for the B-RISK workstation item.

12.4.3.1 Office workstation

Data published by NIST was used to estimate the contents, combustible mass, and heat release rate of the workstations[26]. The workstations included partitions, desk, chair, computer, wastebasket, and papers. The heat release rate reported in the NIST studies was obtained in a calorimeter and compartment effects were not included. The combustible mass was assumed to be 100 kg as measured in the NIST Cook County tests, and primarily made up of ordinary combustible material such as paper, particleboard, and wood, with polyurethane foam in the chair and ABS plastic for the computer components.

The measured HRR from the NIST tests and the theoretical HRR used for the B-RISK workstation item are shown in Figure 12.33. The theoretical HRR was a t^2 fire with a growth time constant of 250 s to 1055 kW (slightly faster than a medium fire) up to a peak HRR of 3400 kW and then exponential decay with a time constant of 0.025 s^{-1}.

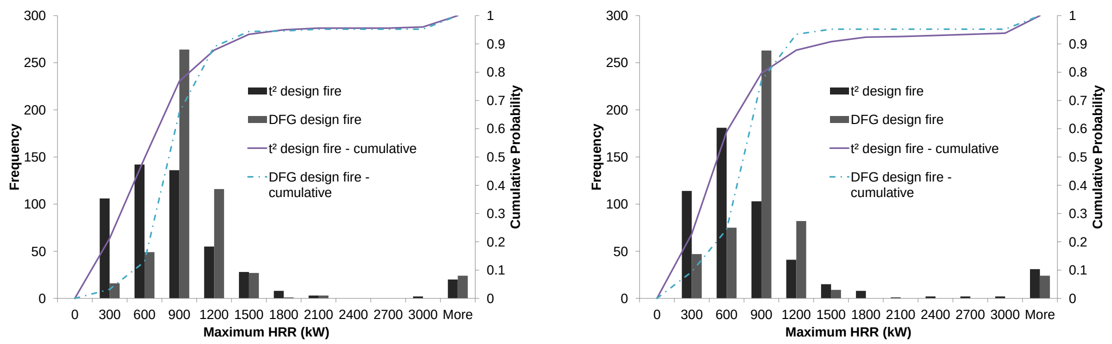
To account for the possibility that either an ordinary combustible material like MDF or paper, plastic like a wastebasket or computer component, or upholstered furniture like the office chair might be the first item ignited in the workstation, three separate items were created with ignition properties for the three types of materials listed above. The ABS, MDF, and PU/polyester foam combination ignition properties were used for the three types of item.

As the office workstation represented a composite item made of several materials, the generic heat of combustion, yields, and radiant loss fraction from C/VM2[25] were used, with uniform distributions representing ±25% of the nominal values.

12.4.4 B-RISK results

12.4.4.1 Comparison between design fires

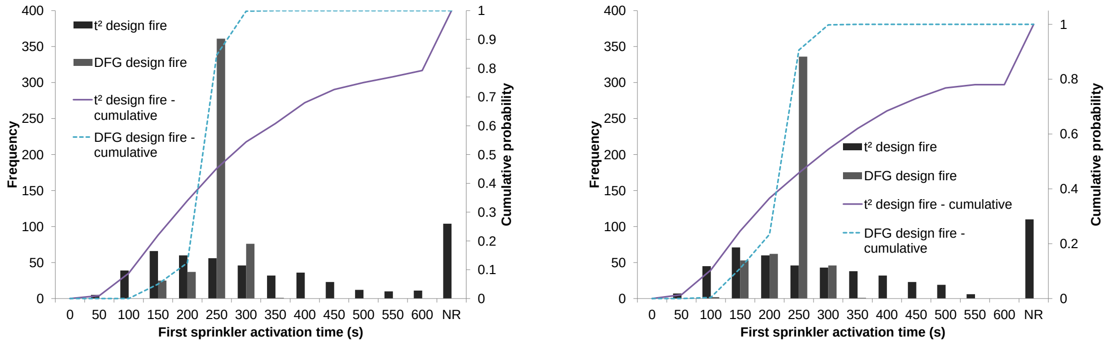
The maximum HRR and sprinkler activation characteristics were compared between the t^2 and DFG design fires. The maximum HRR histograms can be seen in Figure 12.34. The DFG design fire resulted in less iterations with a low maximum HRR.



(a) Existing (b) DTS

Figure 12.34: Comparison of the maximum HRR for the t^2 and DFG design fires.

Histograms comparing the first sprinkler activation times for the t^2 and DFG design fires can be seen in Figure 12.35. The single characteristic HRR curve for the DFG office workstation item resulted in much less spread in sprinkler activation times, grouped tightly around 250 s for both the existing and DTS building configurations.

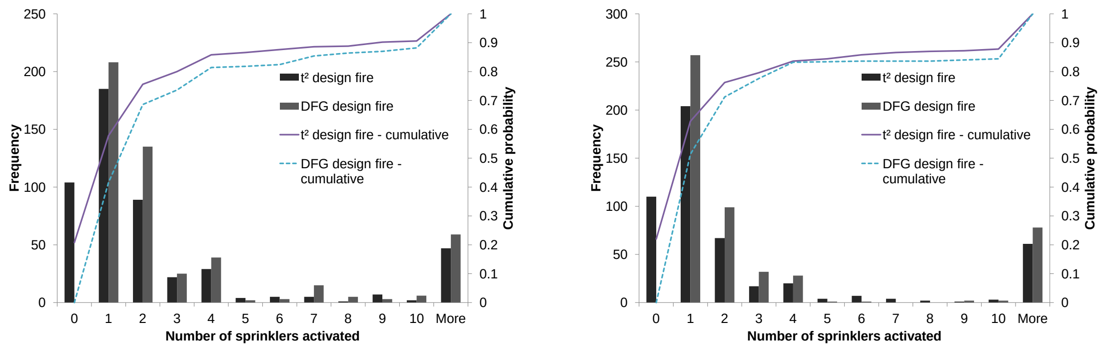


(a) Existing

(b) DTS

Figure 12.35: Comparison of the first sprinkler activation time for the t^2 and DFG design fires. (NR = no response)

A comparison of the number of sprinklers activated for the t^2 and DFG design fires is shown in Figure 12.36. There were no iterations where sprinklers did not activate before the maximum simulation time of 600 s was reached, again because of the fixed HRR for each item. Otherwise, the number of sprinklers activated was consistent between the two design fire approaches.



(a) Existing

(b) DTS

Figure 12.36: Comparison of the number of sprinklers activated for the t^2 and DFG design fires.

The large variation between the two design fire approaches resulted in the decision to compare the tenability in the stairwells using both approaches.

12.4.4.2 Comparison between building configurations using the t^2 design fire

A comparison of the peak HRR for the three building configurations using the t^2 design fire is shown in Figure 12.37. The OH building had a higher probability of lower peak HRRs due to the closer sprinkler spacing causing the sprinklers to activate earlier, as shown in Figure 12.38.

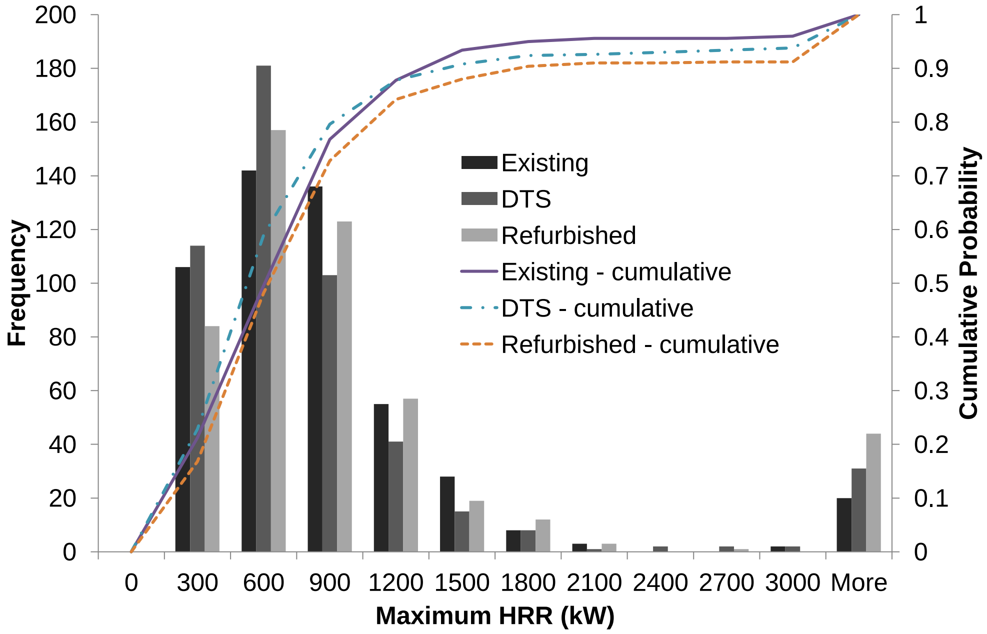


Figure 12.37: Peak HRR for 140 William Street building designs for the t^2 design fire.

A histogram of the number of sprinklers activated for each of the three building designs is shown in Figure 12.39. There was not a significant difference between the ELH and OH sprinkler system designs.

Comparisons of the probability to reaching the visibility criteria for the fire compartment, single stairwells, and both stairwells in each iteration can be seen in Figures 12.40, 12.41, and 12.42, respectively. The refurbished design had a higher probability of the visibility criteria being reached in the fire compartment relative to the existing design, possibly due to the higher reliability of the doors with hold open devices. With the doors closed, the smoke layer would be able to reach a lower height in the fire compartment as it would not be allowed to flow into the adjacent compartments as quickly. The probability of reaching the visibility criteria within the simulated time was low for all buildings, occurring in less than 0.25% of

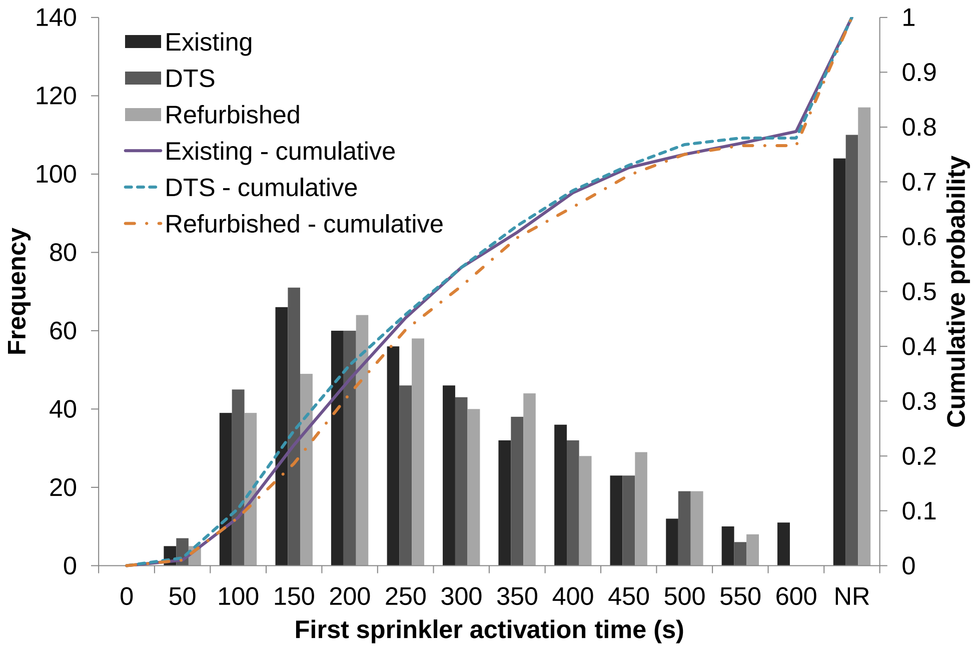


Figure 12.38: Sprinkler activation times for the 140 William Street building designs for the t^2 design fire.

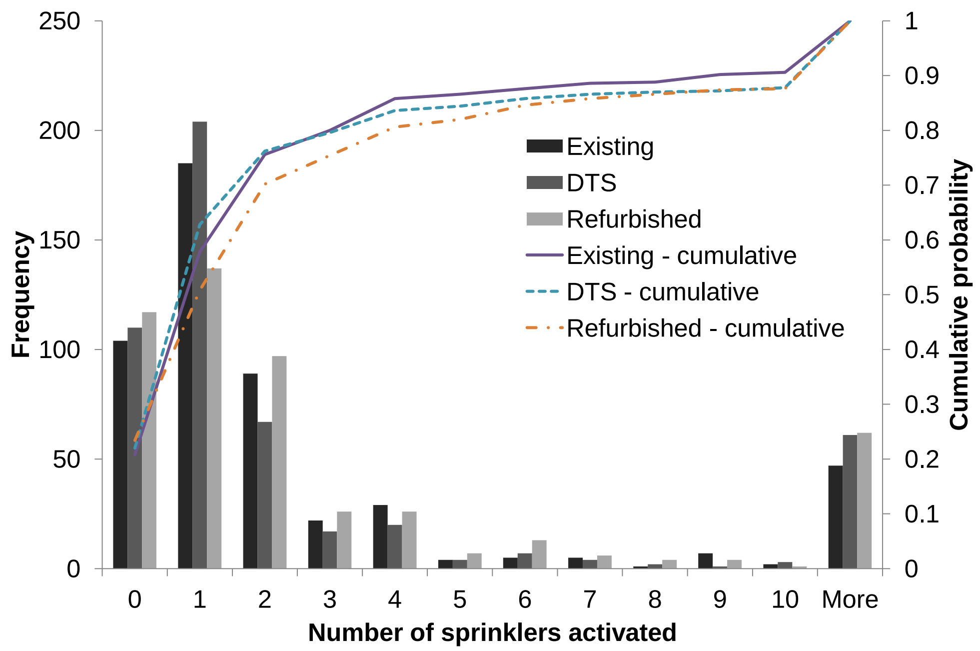


Figure 12.39: Number of sprinklers activated for the 140 William Street building designs for the t^2 design fire.

simulation runs, so the outcome was sensitive to random input parameter selection in individual simulations. The DTS design had significantly higher probability of reaching untenable conditions in the stairwells compared to the existing and refurbished building designs.

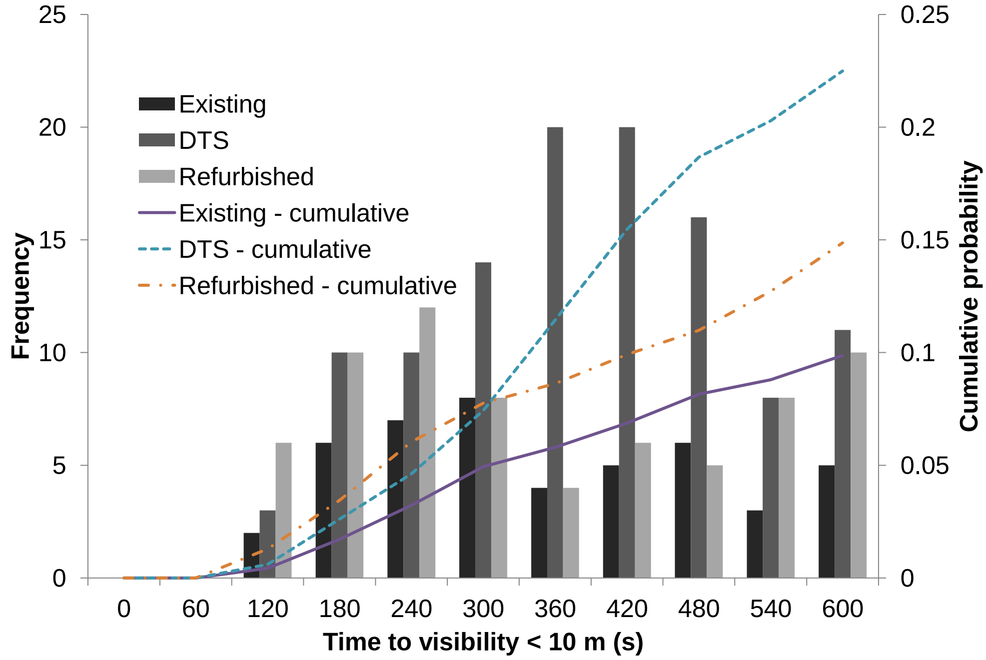


Figure 12.40: Histogram showing the probability of reaching the visibility criteria in the 140 William Street fire compartment for the t^2 design fire.

12.4.4.3 Comparison between building configurations using the DFG design fire

The secondary items ignited for the DFG design fire are shown in Figure 12.43. The DTS building had slightly lower numbers of items ignited, likely due to the closer sprinkler spacing for the OH sprinkler system. Approximately 80% of the iterations for all three building configurations had no items ignited.

The histogram for the time to reach untenability in the fire compartment using the DFG design fire is shown in Figure 12.44. Similar to the t^2 design fire results, the DTS building was more likely to reach the visibility criteria sooner than the existing or refurbished building configuration.

Only two of the iterations using the DFG design fire resulted in the visibility criteria being reached in the existing configuration, compared to 12 for the DTS configuration and one for the refurbished configuration. This indicates again that the

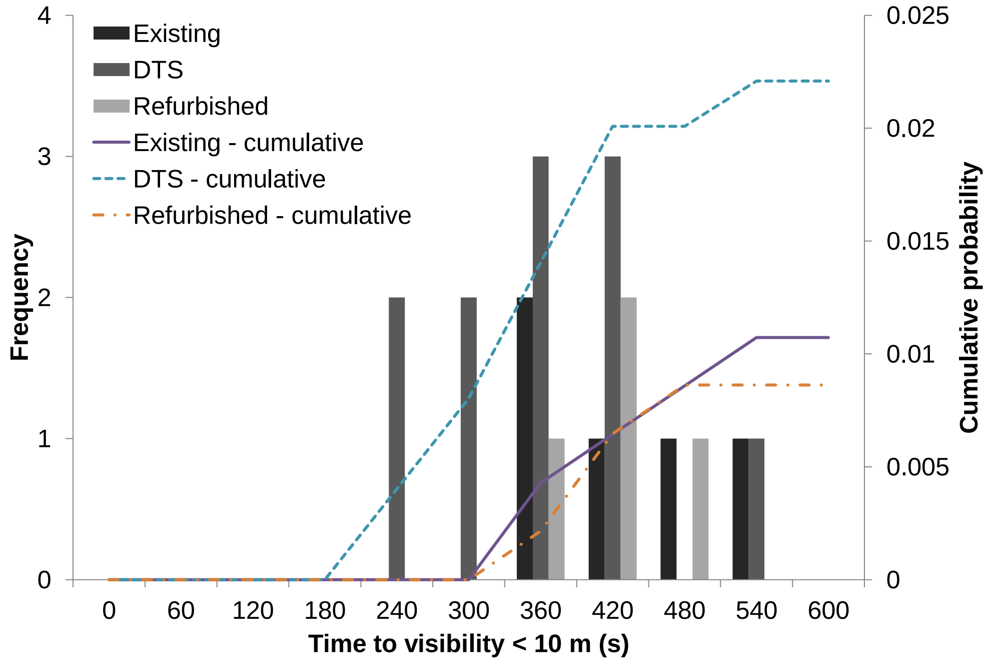


Figure 12.41: Histogram showing the probability of reaching the visibility criteria in a single stair in the 140 William Street building for the t^2 design fire.

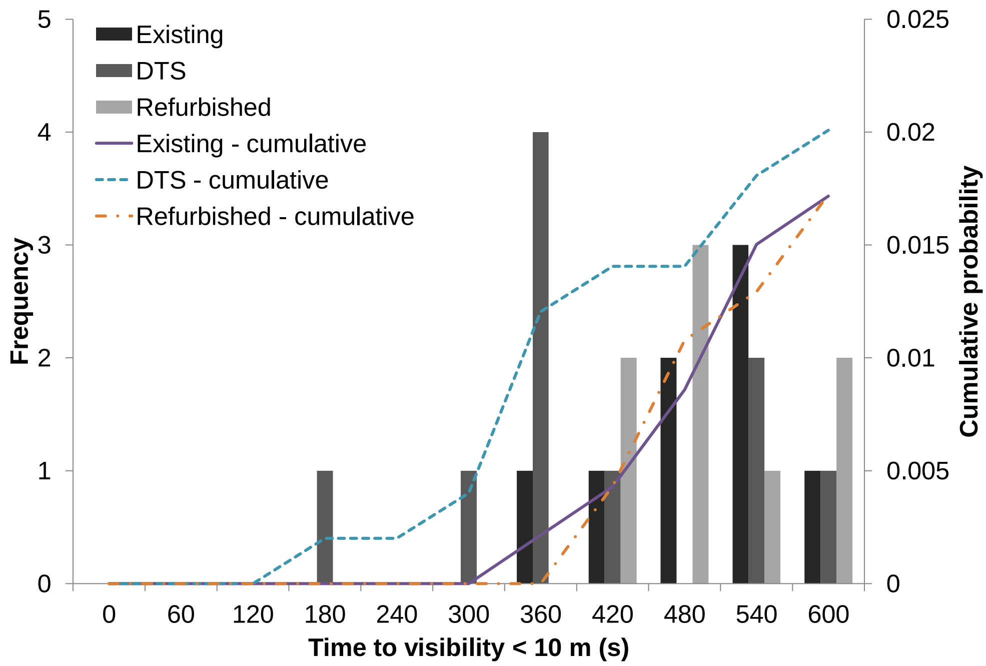


Figure 12.42: Histogram showing the probability of reaching the visibility criteria in both stairs in the 140 William Street building for the t^2 design fire.

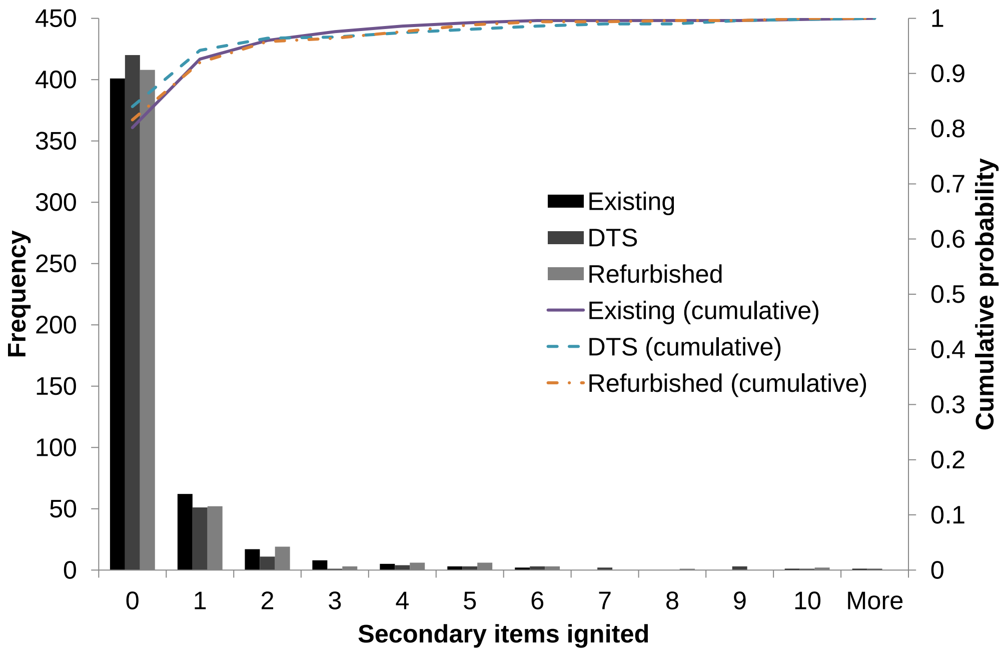


Figure 12.43: Secondary items ignited for the 140 William Street building designs using the DFG design fire.

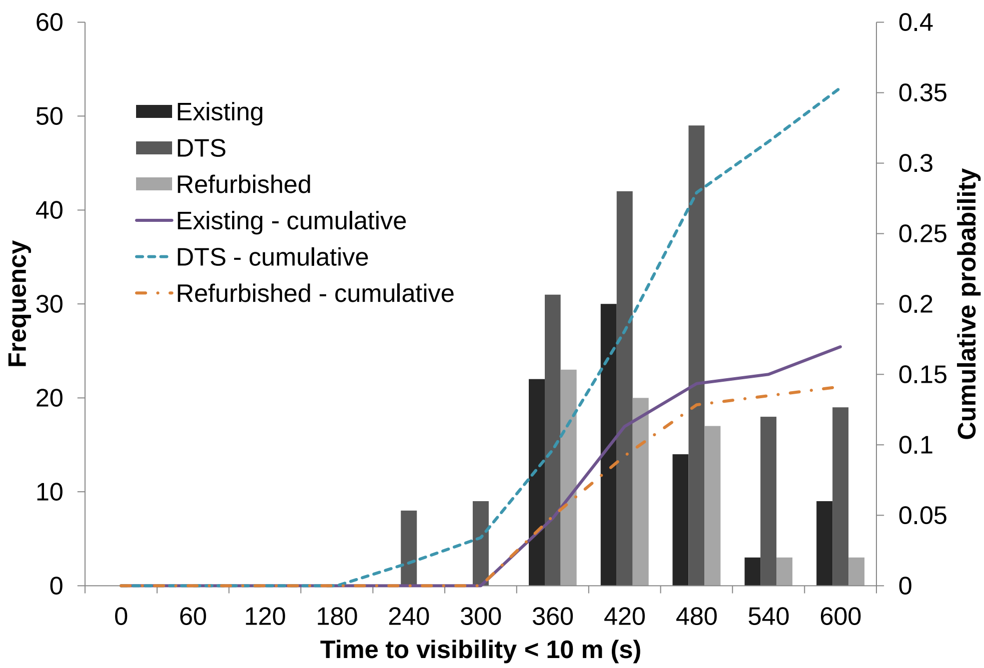


Figure 12.44: Time to reach the visibility criteria in the fire compartment for the 140 William Street building designs using the DFG design fire.

building ranking from lowest to highest fire risk was the DTS, existing, and refurbished building. This conclusion is similar to what was reached in the original risk assessment.

12.5 Conclusions

B-RISK's capabilities for modelling fire safety systems have been demonstrated for two types of buildings, one residential and the other commercial. In its state at the time of writing, B-RISK can provide a probabilistic estimate of the time to untenability for room contents fires. B-RISK does not provide a complete assessment of fire risk, but can be used by fire safety practitioners to make risk-informed decisions along with other information and tools to complete the fire risk picture.

For the purpose of comparatively evaluating fire safety systems, the advanced item-to-item fire spread calculation ability of the design fire generator did not appear to make a substantial difference, although this was likely influenced by the presence of sprinklers which did not allow the majority of the fires to grow to the point where spread to other items would have occurred.

From a tenability analysis standpoint, the B-RISK analysis predicted that the compliant building was safer than the alternative building for the SME design for occupants above the fire floor and less safe for occupants on the fire floor. For the 140 William Street building, the ranking from least safe to most safe using B-RISK matched the original risk assessment (DTS, existing, refurbished). Additional analysis taking other factors such as occupant behaviour and fire service response into consideration would be required to determine the overall comparative level of risk to the building occupants for both buildings.

It appears that a major limiting factor in the ability of the B-RISK tool to evaluate the comparative risk from competing building designs is the lack of good quality information on system effectiveness. This thesis has attempted to address some of the gaps by collecting existing data from the literature, examining recent fire incident data from the NZFS, and developing new methods for collecting data; however there are still missing pieces which will be discussed in the future work section in Chapter 13. It is hoped that more emphasis on collecting high quality information will be achieved by increasing the awareness of the potential value of the improved information.

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Chapter 13

Conclusions, Recommendations, and Future Work

13.1 Conclusions

The following conclusions have been reached as an outcome of this research:

13.1.1 Performance based design requires performance based data

While a paucity of data will likely always be a stumbling block due to the rarity of fire in buildings, it is clear that current practices for collecting fire system effectiveness data are not adequate to support risk-informed, performance-based fire safety building design. Not only does the lack of useful information from fire incident data prevent the adequate assessment of the performance of future designs, it does not provide any insights into the effects on societal fire risk from the transition to performance-based design.

Much of this data needs to come from cooperation with operational staff who are involved with real fires and the ongoing condition of the building. This includes operational fire service personnel, those involved with inspection, testing, and maintenance, and the building staff themselves. If there is no drive for change from fire safety design practitioners to improve the data collection process, who stand to benefit from it in the ability to make more informed decisions on the fire safety performance of building designs, it will not improve because no other stakeholder has the knowledge of what information is required to assess the fire safety of buildings on a performance basis.

In order to generate a large enough body of information, the collection of useful data needs to take place on a sustained, ongoing basis. With modern data analysis capabilities, the accumulating data can be continuously incorporated and evaluated as to its relevance.

13.1.2 New advances in technology can be used to improve fire safety system data collection

A list of recommendations have been made throughout this research to improve the collection of data on system effectiveness. By linking databases for inspection, maintenance, testing, and design data with fire incident data, a much better picture of the factors that influence system performance can be formed. The system performance in a fire can be compared to the original objectives from the design data. Any system deficiencies noted in inspection or testing such as inadequate water supply pressure can be linked to system performance in actual fires.

The availability of inexpensive microcontrollers, sensors, and integrated circuits can allow data to be collected on building elements such as doors, as demonstrated in this thesis. This opens up a potential source of information that would have been uneconomic to collect without recent technological advances.

13.1.3 B-RISK capabilities for considering fire safety system effectiveness

The new fire safety design tool B-RISK includes a range of capabilities for including the effectiveness of fire safety systems. Probabilistic parameters for sprinkler, passive, and smoke management systems are available for reliability and effectiveness. Uncertainty in the time-based response of active systems can be considered with probabilistic parameters for detector response and system effects on the fire. A new hydraulic module can account for the effects of changing water supply flow characteristics.

B-RISK has limitations in considering the effects of systems. The effects of system interactions such as the influence of sprinklers on smoke management systems due to changed smoke characteristics are not included. B-RISK does not include comprehensive capabilities to include the effects of fire on the systems, such as the degradation of structural elements over time. B-RISK is primarily capable of considering the status of systems prior to the time of ignition and during the growth phase before the fire becomes fully developed. The effects of systems on occupant behaviour are not included and vice versa.

At the moment, B-RISK is limited to tenability analysis and should be used in conjunction with other models for occupant and fire service response. A major limitation in the implementation of the fire safety system capabilities in B-RISK that have been developed in this research is the previously defined lack of useful information to enter into the model input parameters.

13.1.4 Maintaining a "consistent level of crudeness" between model and input data

The choice of fire model should be evaluated for the specific purpose that it is being used for in terms of complexity and sources of uncertainty. A zone model may be sufficiently sophisticated for tenability analysis during early fire development for many design applications where there are large sources of uncertainty in the model inputs when considering potential fires over the lifetime of the building. The use of a more complicated model may provide misplaced confidence in the model results if the model input uncertainty is not taken into account.

For the cases where a more complicated deterministic model is justified, sources of uncertainty can be considered by incorporating many of the probabilistic functions from B-RISK with a more sophisticated deterministic model. The use of this type of tool will be limited by available computational resources, as the increased computational requirements of the more sophisticated deterministic model will be multiplied by the number of runs required by the probabilistic component.

13.2 Future work

The following areas of future work would be useful to enhance knowledge of fire safety system effectiveness for risk-informed fire safety design:

- As mentioned in the Conclusions section, data collection on fire safety systems is not ideal for implementation into performance-based design. It would be useful to monitor how fire incident data is being collected in New Zealand and work to improve the systems aspect of this data. A study on the cost/benefit relationship of allocating more resources to data collection would be interesting.

- Experimental work on the effectiveness of sprinklers under different water supply conditions would be useful to provide more information on the minimum supply requirements for effective sprinkler operation.

- Data on passive building element performance is limited and could be expanded. The door position logging devices described in Chapter 9 can be modified to log window position. Window position could be measured with the compass or accelerometer for hinged windows (side and top swinging, respectively) or a linear sensor could be used to track sliding windows. Data on more types of doors could be collected.

- Data on service penetrations in walls and leakage of doors is currently limited, more investigation into this area is warranted. This would require gaining access to service areas of buildings, and thus would be most suited to a person who already has access to these areas.

- Data on smoke management system effectiveness appears to be particularly lacking. A database of buildings in New Zealand that have these systems installed would be useful to track any actual fire incidents that occur in buildings with these systems. Once fires in buildings with these systems have been identified, work to attempt to quantify the performance of the smoke management systems in terms of the fire risk objectives might be possible. One potential area of research might be to identify if pressure measurement is undertaken in buildings with stairwell pressurisation systems and therefore if pressure differential data from both testing and real fire incidents in these buildings is available.

- Interactions between fire safety systems are not well understood and need to be developed further to understand the effects of multiple systems on fire risk in buildings.

- Potential areas for future research for fire safety system effects on evacuation include additional data collection on door negotiation time, detector and alarm activation uncertainty and sensitivity, and smoke control system effects on evacuation (such as increased time to negotiate doors due to differential pressures).

The following areas of future work would be useful to enhance the ability of B-RISK to consider fire safety systems effects for risk-informed fire safety design:

- The ability of B-RISK to consider the effects of systems in later stages of fires could be enhanced by adding models for the performance of passive building elements in post flashover conditions. At the time of writing there is a project planned to expand B-RISK's capabilities to consider the effects of fire on passive building elements.

- If the B-RISK model is integrated with an evacuation model such as EvacuationNZ[1], a study on the system effects on evacuation proceedings would be useful.

- If the B-RISK model is integrated with a fire service response model such as FBIM[2], a study could be conducted using B-RISK on the interactions between fire safety systems and fire service operations.

- The sprinkler thermal response model can be improved by adding the evaporative cooling model developed by Ruffino and diMarzo[3]. Use of this model will require data on how much water can be expected to reach unactivated sprinklers. A set of experiments for this work was originally envisioned as part of this research to provide some of this information, by measuring sprinkler bulb thermal response in the presence of activated sprinklers with water flowing in fire conditions. A method for measuring sprinkler bulb thermal response is described in Chapter 6. The heat release rate would be controlled by using a LPG burner with a flow controller. These experiments were not completed for this work due to the February 22, 2011 Christchurch earthquake, which severely limited laboratory access for approximately six months.

- It may be possible to include the effects of sprinkler spray on fire products such as smoke in B-RISK, if a suitable submodel is available. Work done by Li et al[4,5] may be a starting point.

- A major drawback in the current B-RISK model is that all probabilistic variables are currently treated as independent variables, with no correlation. This may not be a realistic assumption; for example, if maintenance is poor in a building, the reliability of both sprinkler systems and smoke control systems may be low. If the building does not have a policy of keeping doors closed, there may be a higher probability of multiple doors being open. One area of future work may be to add the ability to correlate input variables for B-RISK. However, it is noted that there is enough difficulty in obtaining data for independent variables, obtaining evidence of correlations would be even more difficult and would require additional data collection effort.

- It was observed in the B-RISK case studies that it becomes difficult to resolve low probability, high consequence scenarios such as the simultaneous failure of multiple systems in the context of the overall fire risk. An analysis method could be developed to identify the statistical significance of low probability events occurring in the model.

- Another approach to improve the ability of B-RISK to accurately portray the potential risk impact of low probability, high consequence scenarios might be to develop a method to conduct secondary sets of runs using B-RISK or another model based on the specific input parameter values that result in these scenarios. The information from this secondary analysis could then be integrated back into the overall risk picture. This would focus computational effort on the situations where high consequences can occur while still evaluating overall risk adequately.

Some of the future work listed above, particularly where the B-RISK model would be used or improved, is suitable for postgraduate Fire Engineering projects. However, improving data collection from actual buildings and fire incidents should be ongoing and while aspects of it can be completed by students, it has the best chance of success if it is championed by persons active in the fire safety field on a full time basis.

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APPENDIX A

HYDRAULIC MODEL DEVELOPMENT AND VERIFICATION

A.1 Hydraulic model

A hydraulic model was developed in Excel 2007 to solve the flow and pressure in simple sprinkler systems for analysing the effects of pressure reduction on sprinkler system performance. The model was adapted for use with sprinkler systems from an existing model described in the book Hydraulics of Pipeline Systems[1]. Both metric and imperial units can be used.

The hydraulic model was then transferred to VB.net for incorporation into the risk-informed design fire tool. The sprinkler system was still defined in Excel, but a routine was developed to export the sprinkler system to an XML file which could be read by the VB.net version of the model. The Excel figures in this appendix correspond to the 35 m static head NZS4541:2007[2] commercial ELH minimum water supply discussed in Chapter 7. The hydraulic model described here can cope with different room geometries and sprinkler spacings, although B-RISK is currently limited to right rectangular prisms for the room geometry. Physically looped pipe systems can not be handled with this model.

A.1.1 Sprinkler system definition

The sprinkler system is defined in three phases: nodes, pipes, and loops. Each sprinkler head, tee, and water supply source are assigned a node number. The number of junctions is equal to the total number of nodes minus the water supply nodes. A parameter defines the type of node:

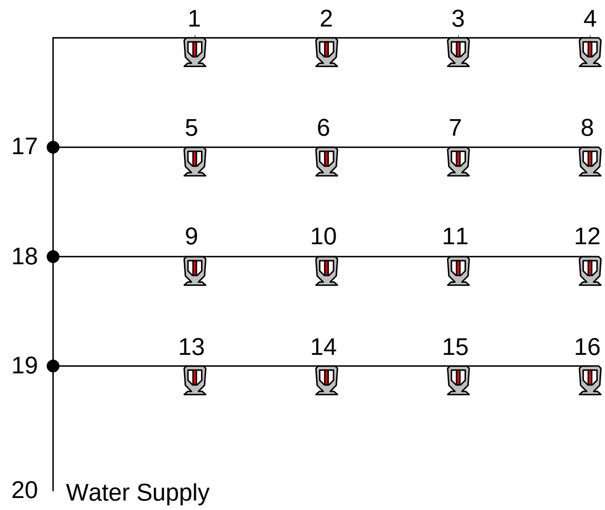


Figure A.1: Node numbering for an example sprinkler system in the hydraulic model.

- 0: inactive sprinkler
- 1: activated sprinkler
- 2: tee or junction
- 3: water supply (constant head)
- 4: water supply (quadratic function relating head and flow)

Nodes are typically assigned as shown in Figure A.1, with the sprinklers, then tees or junctions, then the water supply numbered consecutively from node 1. Sprinklers are assigned a sprinkler discharge coefficient (K) in units of $\frac{l/min}{\sqrt{kPa}}$ or $\frac{gpm}{\sqrt{psi}}$. Each node can be assigned an elevation. Figure A.2 shows how the nodes for the example system in Figure A.1 were assigned. If a quadratic water supply node was chosen, water supply flow and pressure data were plotted and quadratic coefficient parameters were determined by the Excel trendline curve fit function, as shown in Figure A.3.

After the nodes were defined, the pipe connections between nodes were defined. Pipes were systematically defined by starting at defining the downstream pipes from each consecutive node as shown in Figure A.4. Each “pipe” could be composed of up to 4 pipe sections to account for fittings, changes in diameter, and multiple lengths.

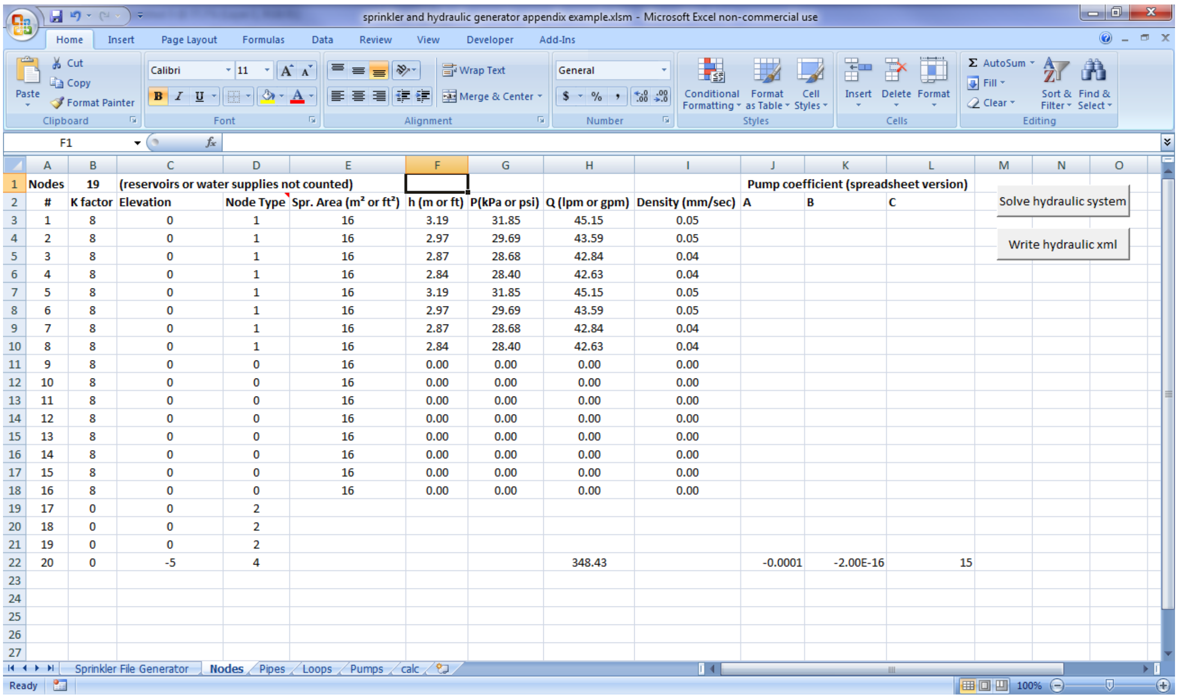


Figure A.2: The worksheet where the node numbers and characteristics were assigned.

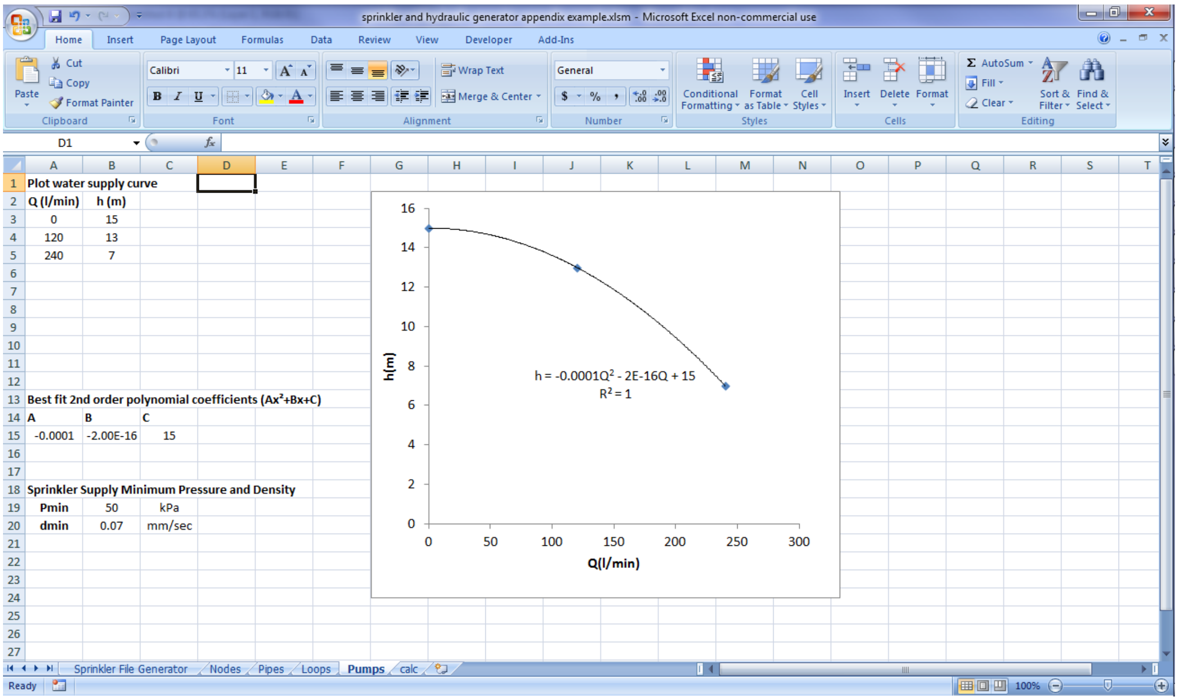
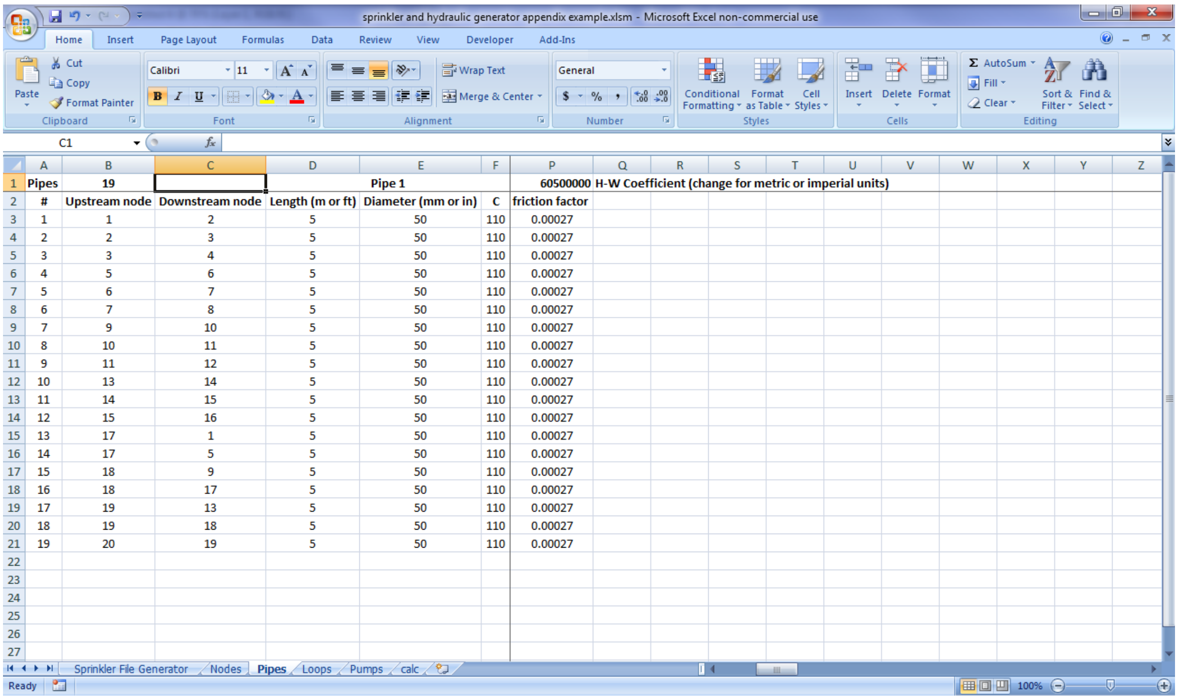


Figure A.3: A water supply worksheet was used to plot water supply flow and pressure points and curve fit a quadratic function.



	A	B	C	D	E	F	P	Q
1	Pipes	19			Pipe 1		60500000	H-W Coefficient (change for metric or imperial units)
2	#	Upstream node	Downstream node	Length (m or ft)	Diameter (mm or in)	C	friction factor	
3	1	1	2	5	50	110	0.00027	
4	2	2	3	5	50	110	0.00027	
5	3	3	4	5	50	110	0.00027	
6	4	5	6	5	50	110	0.00027	
7	5	6	7	5	50	110	0.00027	
8	6	7	8	5	50	110	0.00027	
9	7	9	10	5	50	110	0.00027	
10	8	10	11	5	50	110	0.00027	
11	9	11	12	5	50	110	0.00027	
12	10	13	14	5	50	110	0.00027	
13	11	14	15	5	50	110	0.00027	
14	12	15	16	5	50	110	0.00027	
15	13	17	1	5	50	110	0.00027	
16	14	17	5	5	50	110	0.00027	
17	15	18	9	5	50	110	0.00027	
18	16	18	17	5	50	110	0.00027	
19	17	19	13	5	50	110	0.00027	
20	18	19	18	5	50	110	0.00027	
21	19	20	19	5	50	110	0.00027	

Figure A.4: The connections between nodes were defined as pipes.

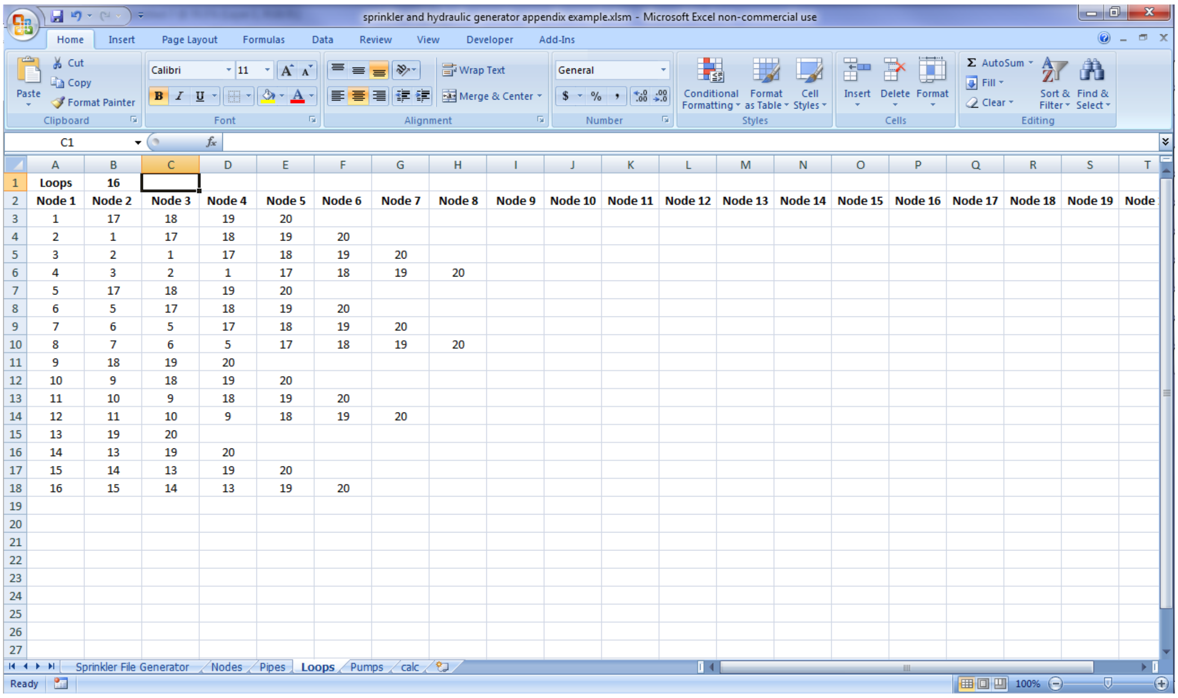
Once the pipes were defined, energy equation loops were defined in the Loops worksheet as shown in Figure A.5. A loop was required for each sprinkler, and included all of the nodes from the sprinkler back to the water supply.

A.1.2 Hydraulic model physics

The pressures and flows in the hydraulic model were solved by solving the continuity and energy equations for the sprinkler system network. A continuity equation was set up for a control volume around each node except the water supply as shown in Figure A.6. If the node was downstream, the flow sign was changed to negative. Energy equations were set up for each loop as shown in Figure A.7.

The pressure loss for the pipe sections and sprinklers was calculated using the Hazen Williams equation and sprinkler loss equation respectively as shown below in metric form, which is recommended by NZS4541:2007.

$$\Delta P = \frac{0.605 \times 10^8 \times Q^{1.85}}{C^{1.85} d^{4.87}} \tag{A.1}$$



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Loops	16																		
2	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9	Node 10	Node 11	Node 12	Node 13	Node 14	Node 15	Node 16	Node 17	Node 18	Node 19	Node
3	1	17	18	19	20															
4	2	1	17	18	19	20														
5	3	2	1	17	18	19	20													
6	4	3	2	1	17	18	19	20												
7	5	17	18	19	20															
8	6	5	17	18	19	20														
9	7	6	5	17	18	19	20													
10	8	7	6	5	17	18	19	20												
11	9	18	19	20																
12	10	9	18	19	20															
13	11	10	9	18	19	20														
14	12	11	10	9	18	19	20													
15	13	19	20																	
16	14	13	19	20																
17	15	14	13	19	20															
18	16	15	14	13	19	20														

Figure A.5: Loops were defined as required to calculate the conservation of energy equation.

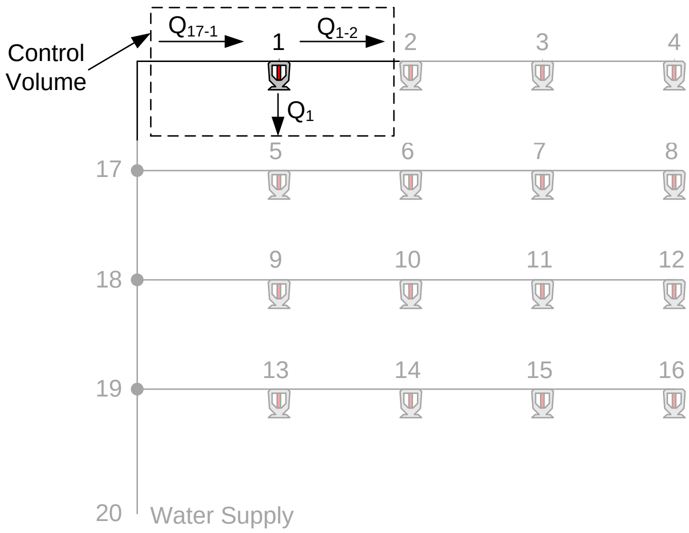


Figure A.6: Continuity equations were defined for each node. For the node shown in this example $Q_1 = Q_{17-1} - Q_{1-2}$.

$$\Delta P = \left(\frac{Q}{K}\right)^2 \tag{A.2}$$

In this implementation, the total pressure is used and the velocity pressure is

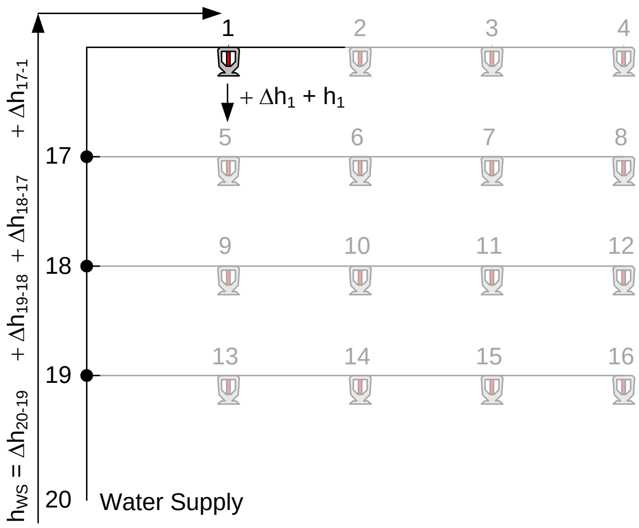


Figure A.7: Energy loop equations were set up for each active sprinkler. For the loop shown in this example $h_{WS} = \Delta h_{20-19} + \Delta h_{19-18} + \Delta h_{18-17} + \Delta h_{17-1} + \Delta h_1 + h_1$.

not considered, as is allowed by NZS4541:2007. The pressure loss was converted to head loss by the formula NZS4541:2007 recommends:

$$P = 10 \times h \tag{A.3}$$

where P is in kPa and h is in m, which is an approximation of the usual form:

$$P = \rho g h \tag{A.4}$$

Once the continuity and energy loss equations were found, the system of continuity and energy loop equations were rewritten into the form

$$\mathbf{f}(Q_{pipe\,1}, ...Q_{pipe\,n}, Q_{sprinkler\,1}, ...Q_{sprinkler\,m}) = 0 \tag{A.5}$$

where **f** is a column vector of the continuity and energy loop equations, n is the total number of pipes, and m is the total number of active sprinklers. The roots of the equations in **f** were solved using the Newton method as described by Larock et al[1], which uses the equation

Sprinkler	Gagnon Q (gpm)	Model Q (gpm)	% Difference
1	18.00	17.99	.08%
2	19.08	19.07	.05%
3	20.16	20.10	.30%
4	22.32	22.22	.43%
Total Flow	264.93	265.03	.04%

Table A.1: Comparison of model results to hand calculated results for Gagnon example.

$$\mathbf{x_{new}} = \mathbf{x_{old}} - \mathbf{D^{-1}f} \tag{A.6}$$

to provide iterative approximations of the roots $\mathbf{x}$ using the product of the inverse of the Jacobian matrix $\mathbf{D}$ of $\mathbf{f}$ and $\mathbf{f}$. The Jacobian matrix is defined as shown here:

$$\mathbf{D} = \begin{bmatrix} \frac{\partial f_1}{\partial Q_{pipe\ 1}} & \cdots & \frac{\partial f_1}{\partial Q_{sprinkler\ m}} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_{n+m}}{\partial Q_{pipe\ 1}} & \cdots & \frac{\partial f_{n+m}}{\partial Q_{sprinkler\ m}} \end{bmatrix} \tag{A.7}$$

The inverse of the Jacobian matrix is found by using Gauss-Jordan Elimination in the VB.net implementation of the hydraulic model and by the built in function MINVERSE in the Excel implementation.

A.2 Hydraulic model verification

The model was verified by reproducing the example on pages 148 to 157 from Gagnon[3]. A comparison of the flow rates for the first 4 sprinklers and the total flow rate is shown in Table A.1. The flow rates were all within 0.5% and the differences are possibly due to rounding practices used in the hand calculations.

A.3 Visual Basic hydraulic module

The source code for the Visual Basic hydraulic module is included in the following pages.

D:\Branzfire.NET 28092011\hydraulic.vb 1

```
Imports System.Xml
Imports System.Xml.Linq
Imports System.Xml.Serialization
Imports System.IO
Imports System.Math

Module hydraulic

    Dim numvars As Integer      'Number of variables to be solved for (flow rates)
    Dim numjunct As Integer     'Number of junctions (continuity equations to be solved)
    Dim actsprinklers As Integer    'Number of activated sprinklers
    Dim opensprink As Integer       'Current open sprinkler
    Dim numsprink As Integer        'Total number of sprinklers
    Dim hpconv As Double            'Conversion factor for using metric or imperial units
    Dim numnodes As Integer         'Total number of nodes
    Dim numloops As Integer         'Total number of loops
    Dim numpipes As Integer         'Total number of pipes

    Dim SPmin As Double         'Minimum P as specified by the sprinkler standard
    Dim SDmin As Double         'Minimum density as specified by the sprinkler standard


    Public Sub calc_hyd(ByVal tim As Double)

        'This function is used to calculate the hydraulic pressures and flows in a simple
        'sprinkler network. The network can have branches, but pipe loops are not handled.
        'The required hydraulic network parameters are read in from the read_hyd_xml
        'function. Hydraulic equations are set up by the calc_hyd_eq function, and the
        'Jacobian matrix is inverted using the invertM function.


        Dim D(,) As Double      'Jacobian matrix
        Dim invD(,) As Double   'Inverted Jacobian matrix
        Dim F() As Double       'Vector of continuity and energy equations
        Dim xold() As Double    'Vector of flow rates
        Dim dx() As Double      'Change in flow rate vector for Newton method

        Dim merr As Double      'maximum error
        Dim err As Double       'error variable
        Dim maxiter As Integer  'Maximum number of iterations


        Dim i As Integer
        Dim j As Integer
        Dim k As Integer
        Dim iter As Integer     'Current iteration
        Dim iguess As Integer   'Initial guess for sprinkler flows (required by Newton
    Method)
        Dim Qmin As Double      'Minimum Q (for calculating minimum hydraulic density)
        Dim Pmin As Double      'Minimum P (for estimating when sprinklers are no longer
    effective)
        Dim hyddensity As Double 'Sprinkler spray density
        Dim actsprinklers() As Integer  'Vector to determine which sprinklers are active


        'Initial guess for sprinkler flow (convergence is sensitive to this value w/ Newton
    method)

        iguess = 18

        hpconv = 10 '(.433 imperial units) (10 metric units)

        'Initialize maximum error and maximum number of iterations

        maxiter = 100
        merr = 0.0001


        'Gets total number of active sprinklers and number of continuity equations required
```

```
        numsprink = 0
        numjunct = 0
        j = 0

        For i = 0 To numnodes - 1
            If nodes(i, 3) < 2 Then
                numsprink = numsprink + 1
            End If

            If nodes(i, 3) = 1 Then
                ReDim Preserve actsprinklers(j)
                actsprinklers(j) = nodes(i, 0)           'Gives a vector of the activated
    sprinklers, for calculating K factor and Area
                j = j + 1
            End If

            If nodes(i, 3) < 3 Then
                numjunct = numjunct + 1
            End If
        Next

        'Total number of unknowns to solve for

        numvars = numjunct + actsprinklers.Length

        ReDim invD(numvars - 1, numvars - 1)
        ReDim D(numvars - 1, numvars - 1)
        ReDim F(numvars - 1)
        ReDim xold(numvars - 1)
        ReDim dx(numvars - 1)

        'Set up initial guess for flow rates

        For i = 0 To numvars - 1
            xold(i) = iguess
        Next i


        'Iterate for newton's method

        For iter = 1 To maxiter

            'Calculate system equations
            calc_hyd_eq(D, F, xold)

            invertM(D, invD)        'Invert matrix
            err = 0
            For j = 0 To numvars - 1
                dx(j) = 0
                For k = 0 To numvars - 1
                    dx(j) = dx(j) + invD(j, k) * F(k)
                Next
                err = (err ^ 2 + dx(j) ^ 2) ^ 0.5
                xold(j) = xold(j) - dx(j)
            Next
            If err < merr Then
                Exit For
            End If
        Next iter

        'Go through sprinkler flow rates, find minimum density and pressure
        Qmin = xold(numjunct - 1)
        hdmin = Qmin / nodes(actsprinklers(0) - 1, 4) / 60
        Pmin = 1 / (nodes(actsprinklers(0) - 1, 1) ^ 2) * Qmin * Abs(Qmin)
        For j = 0 To actsprinklers.Length - 1
            hyddensity = xold(numjunct + j) / nodes(actsprinklers(j) - 1, 4) / 60
            If xold(numjunct + j) < Qmin Then
                Qmin = xold(numjunct + j)
```

```
                Pmin = 1 / (nodes(actsprinklers(j) - 1, 1) ^ 2) * Qmin * Abs(Qmin) 
'calculate minimum sprinkler pressure
            End If
            If hyddensity < hdmin Then
                hdmin = hyddensity
            End If
        Next


        'Checks to see if the minimum sprinkler pressure or spray density are being supplied

        If (Pmin < SPmin) And (minsupplyflag = 0) Then
            minsupplyflag = 1
            mstime = tim
            mssprinklers = actsprinklers.Length

        End If

        If (hdmin < SDmin) And (minsupplyflag = 0) Then
            minsupplyflag = 2
            mstime = tim
            mssprinklers = actsprinklers.Length
        End If



    End Sub

    Public Sub calc_hyd_eq(ByRef D(,) As Double, ByRef F() As Double, ByVal xold() As Double)

        'This function calculates the required Jacobian matrix D and continuity/energy 
    equation vector
        'F as required for the calc_hyd to solve the hydraulic system of equations using 
    Newton's method.

        ReDim D(numvars - 1, numvars - 1)
        ReDim F(numvars - 1)

        opensprink = 0

        'Continuity equations

        For i = 0 To numjunct - 1

            If nodes(i, 3) > 2 Then      'No continuity equation for water sources
                Exit For
            End If

            For j = 0 To numpipes - 1
                If pipes(j, 1) = nodes(i, 0) Then     'continuity node is upstream
                    D(i, j) = 1
                    F(i) = F(i) + xold(j)
                ElseIf pipes(j, 2) = nodes(i, 0) Then  'continuity node is downstream
                    D(i, j) = -1
                    F(i) = F(i) - xold(j)
                End If
            Next j
            If nodes(i, 3) = 1 Then              'adds sprinkler flow if the sprinkler is 
    active
                opensprink = opensprink + 1
                D(i, numjunct + opensprink - 1) = 1
                F(i) = F(i) + xold(opensprink + numjunct - 1)

            End If

        Next i

        'Energy loop equations
```

```
        opensprink = 0

        For i = 0 To numloops - 1
            If nodes(i, 3) = 1 Then             'Creates a energy loop if sprinklers are open
                opensprink = opensprink + 1
                D(opensprink + numjunct - 1, opensprink + numjunct - 1) = 2 / (hpconv * nodes↙
(i, 1) ^ 2) * xold(opensprink + numjunct - 1)
                F(opensprink + numjunct - 1) = F(opensprink + numjunct - 1) + 1 / (hpconv * ↙
nodes(i, 1) ^ 2) * xold(opensprink + numjunct - 1) * System.Math.Abs(xold(opensprink + ↙
numjunct - 1))

                For j = 2 To loops(i, 1)        'goes through loop nodes to fill energy ↙
equation

                    For k = 0 To numpipes - 1
                        If pipes(k, 1) = loops(i, j) Then
                            If pipes(k, 2) = loops(i, j + 1) Then
                                D(opensprink + numjunct - 1, k) = D(opensprink + numjunct - 1↙
, k) - 1.85 / hpconv * pipes(k, 3) * xold(k) * System.Math.Abs(xold(k)) ^ (-0.15)
                                F(opensprink + numjunct - 1) = F(opensprink + numjunct - 1) -↙
 pipes(k, 3) * xold(k) * System.Math.Abs(xold(k)) ^ 0.85

                                'Checks to see if upstream node is a reservoir or pump
                                If nodes(pipes(k, 1) - 1, 3) = 3 Then 'Reservoir

                                    F(opensprink + numjunct - 1) = F(opensprink + numjunct - ↙
1) - nodes(pipes(k, 1) - 1, 2)

                                ElseIf nodes(pipes(k, 1) - 1, 3) = 4 Then 'Pump

                                    D(opensprink + numjunct - 1, k) = D(opensprink + numjunct↙
 - 1, k) - (2 * supplycurve(0) * xold(k) + supplycurve(1))

                                    F(opensprink + numjunct - 1) = F(opensprink + numjunct - ↙
1) - (supplycurve(0) * xold(k) * Abs(xold(k)) + supplycurve(1) * xold(k) + supplycurve(2)↙
 + nodes(pipes(k, 1) - 1, 2))

                                End If
                            End If
                        End If

                        'Finds the pipe if the next pipe node is defined as the downstream ↙
node

                        If pipes(k, 2) = loops(i, j) Then
                            If pipes(k, 1) = loops(i, j + 1) Then
                                D(opensprink + numjunct - 1, k) = D(opensprink + numjunct - 1↙
, k) + 1.85 / hpconv * pipes(k, 3) * xold(k) * System.Math.Abs(xold(k)) ^ (-0.15)
                                F(opensprink + numjunct - 1) = F(opensprink + numjunct - 1) +↙
 1 / hpconv * pipes(k, 3) * xold(k) * System.Math.Abs(xold(k)) ^ 0.85

                                'Checks to see if upstream node is a reservoir or pump
                                If nodes(pipes(k, 1) - 1, 3) = 3 Then 'Reservoir

                                    F(opensprink + numjunct - 1) = F(opensprink + numjunct - ↙
1) - nodes(pipes(k, 1) - 1, 2)

                                ElseIf nodes(pipes(k, 1) - 1, 3) = 4 Then 'Pump

                                    D(opensprink + numjunct - 1, k) = D(opensprink + numjunct↙
 - 1, k) - (2 * supplycurve(0) * xold(k) + supplycurve(1))

                                    F(opensprink + numjunct - 1) = F(opensprink + numjunct - ↙
1) - (supplycurve(0) * xold(k) * Abs(xold(k)) + supplycurve(1) * xold(k) + supplycurve(2)↙
 + nodes(pipes(k, 1) - 1, 2))

                                End If
                            End If
                        End If
```

```
                Next k
            Next j
        End If
    Next i

End Sub


Public Sub invertM(ByVal D(,) As Double, ByRef invD(,) As Double)

    'A function designed to invert the Jacobian matrix D for calc_hyd.

    Dim i As Integer
    Dim j As Integer
    Dim k As Integer
    Dim Atemp(,) As Double
    Dim rows As Integer
    Dim cols As Integer
    Dim col1 As Integer
    Dim maxVal As Double
    Dim maxInd As Double
    Dim temp As Double
    Dim hold(,) As Double

    rows = D.GetUpperBound(0)
    col1 = D.GetUpperBound(1)

    cols = col1 + col1 + 1

    ReDim Atemp(rows, cols)
    ReDim hold(rows, cols)

    'Augment matrix with identity matrix
    For i = 0 To rows
        For j = 0 To rows
            Atemp(i, j) = D(i, j)
            Atemp(i, j + rows + 1) = 0.0
        Next j
        Atemp(i, i + rows + 1) = 1.0
    Next i

    For i = 0 To rows

        maxVal = Atemp(i, i)
        maxInd = i
        ' Sort procedure finds the greatest leading value
        For j = i + 1 To rows
            If Abs(Atemp(j, i)) > Abs(maxVal) Then
                maxVal = Atemp(j, i)
                maxInd = j
            End If
        Next j

        If maxVal = 0 Then
            MsgBox(Prompt:="Matrix is singular!", Title:="Error")
            Exit Sub
        End If

        'Set pivot equal to 1 and swap rows if necessary
        For j = i To cols
            'row i into temporary storage if swap is needed
            temp = Atemp(i, j)
            'data from row max_ind into row i and divide by maxval
            Atemp(i, j) = Atemp(maxInd, j) / maxVal
            'Swap the max_ind row with row i (if necessary)
            If maxInd <> i Then Atemp(maxInd, j) = temp
        Next j
```

```
            'Perform row operations to produce reduced row-echelon form
            For k = 0 To rows
                If k <> i Then              'Not the pivot
                    'store multiple of row
                    For j = 0 To cols
                        hold(k, j) = -Atemp(k, i) * Atemp(i, j)
                    Next j
                    'add together and replace the row
                    For j = 0 To cols
                        Atemp(k, j) = Atemp(k, j) + hold(k, j)
                    Next j
                End If
            Next k
        Next i

        For i = 0 To rows
            For j = col1 + 1 To cols
                invD(i, j - (col1 + 1)) = Atemp(i, j)
            Next j
        Next i


    End Sub



    Public Sub read_hyd_xml()

        'This function reads in a hydraulic network definition xml file as defined
        'in the spreadsheet Hydraulic Solver.
        'A line in this file specifies the file name and path of the file to be used.

        Dim opendatafile As String
        Dim i As Integer
        Dim j As Integer
        Dim checkval As Double
        Dim maxnodes As Integer 'Maximum number of nodes in loops
        Dim myfile As String
        Dim pumppresent As Integer '0 for not present, 1 for present

        'Removed New_File() - opens a new file using defaults - BAD
        pumppresent = 0


        'Path and name of hydraulic system definition file.

        opendatafile = RiskDataDirectory & "hydraulic.xml"


        If opendatafile <> "" Then

            'returns filename without path if it exists
            myfile = Path.GetFileName(opendatafile)

            If myfile <> "" Then

                Dim myXmlSettings As New XmlReaderSettings()
                myXmlSettings.IgnoreComments = True
                myXmlSettings.IgnoreWhitespace = True

                Using DFR As XmlReader = XmlReader.Create(opendatafile, myXmlSettings)
                    DFR.Read()
                    DFR.ReadStartElement("hydraulic_def")

                    'Write Nodes

                    DFR.ReadStartElement("Nodes")
                    numnodes = DFR.ReadElementString
```

```
                    ReDim nodes(numnodes - 1, 4)
                    For i = 0 To numnodes - 1
                        For j = 0 To 4
                            nodes(i, j) = DFR.ReadElementString
                        Next j
                        If nodes(i, 3) = 4 Then
                            pumppresent = 1                'Sets pumppresent flag to 1 if
    one of the nodes is a pump (4)
                        End If
                        DFR.ReadEndElement()
                    Next i
                    DFR.ReadEndElement()

                    'Write pipes

                    DFR.ReadStartElement("Pipes")
                    numpipes = DFR.ReadElementString
                    ReDim pipes(numpipes - 1, 3)
                    For i = 0 To numpipes - 1
                        For j = 0 To 3
                            pipes(i, j) = DFR.ReadElementString
                        Next j
                        DFR.ReadEndElement()
                    Next i
                    DFR.ReadEndElement()

                    'Write loops

                    DFR.ReadStartElement("Loops")
                    numloops = DFR.ReadElementString
                    maxnodes = DFR.ReadElementString
                    ReDim loops(numloops - 1, maxnodes + 1)
                    For i = 0 To numloops - 1
                        For j = 0 To 1
                            loops(i, j) = DFR.ReadElementString
                        Next j

                        For j = 2 To maxnodes + 1
                            If j < loops(i, 1) + 2 Then
                                checkval = DFR.ReadElementString
                            Else
                                Exit For
                            End If

                            loops(i, j) = checkval

                        Next
                        DFR.ReadEndElement()
                    Next i
                    DFR.ReadEndElement() 'Clear <Loops>

                    'Read minimum supply criteria

                    DFR.ReadStartElement("Minimum_supply")
                    SPmin = DFR.ReadElementString
                    SDmin = DFR.ReadElementString
                    DFR.ReadEndElement() 'Clear <Minimum_supply>

                    'Read quadratic supply (eg. pump) information
                    If pumppresent = 1 Then
                        ReDim supplycurve(2)
                        DFR.ReadStartElement("Supply")
                        For i = 0 To 2
                            supplycurve(i) = DFR.ReadElementString
                        Next i
                        DFR.ReadEndElement() 'Clear <Supply>
                    End If
```

```
                    DFR.ReadEndElement() 'Clear <hydraulic_def>

                End Using
            End If
        End If

    End Sub


End Module
```

References

[1] Larock, B. E., Jeppson, R. W., and Watters, G. Z. (2000). *Hydraulics of Pipeline Systems*. CRC Press.

[2] Standards New Zealand (2007). *NZS 4541:2007 - Automatic Fire Sprinkler Systems*. Wellington, NZ.

[3] Gagnon, R. M. (1997). *Design of Water-Based Fire Protection Systems*. Delmar Publishers, Albany, New York.

Appendix B

ISO 9705 Compartment Fire Test Ceiling Jet and Sprinkler Data

The figures in this appendix show the modified sprinkler temperature response, ceiling jet temperature and velocity, and sprinkler response time for the standard sprinklers. Ceiling jet velocities were not recorded for tests A1 to A3. The tests are described in Chapter 6.

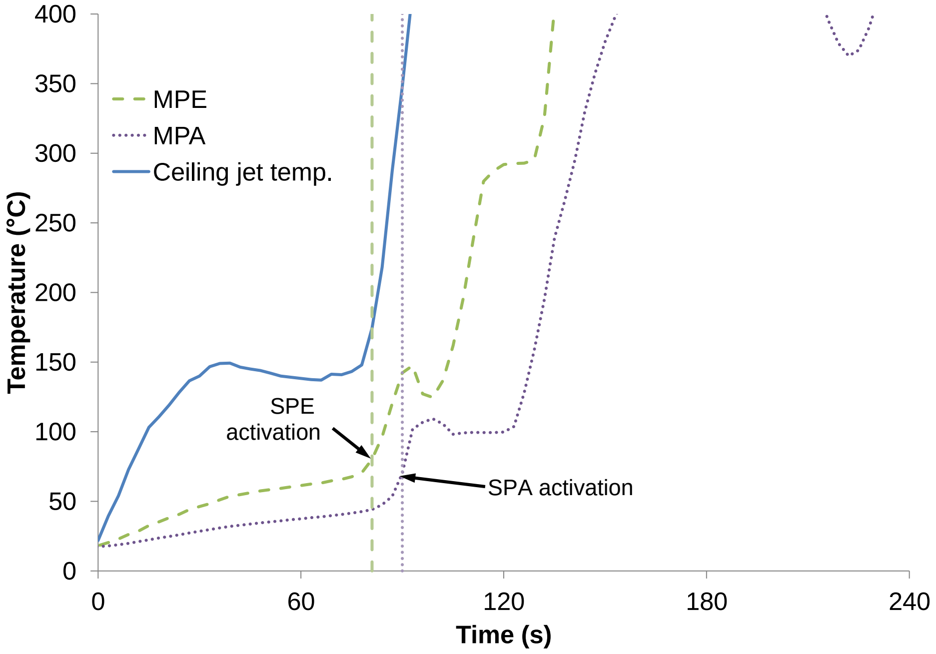


Figure B.1: Modified sprinkler temperature response, ceiling jet temperature, and standard sprinkler response time for compartment fire test A1.

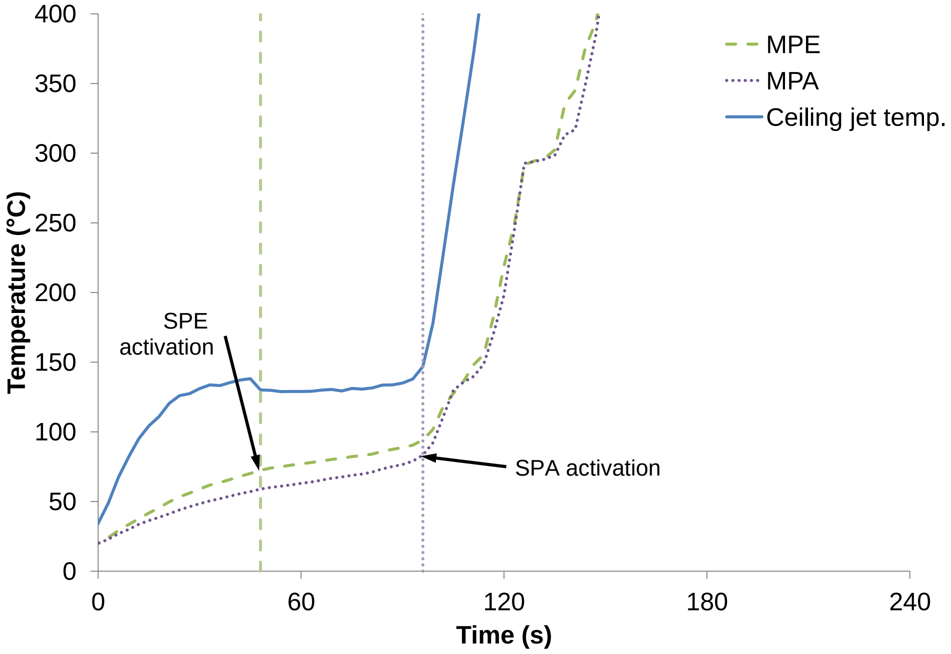


Figure B.2: Modified sprinkler temperature response, ceiling jet temperature, and standard sprinkler response time for compartment fire test A2.

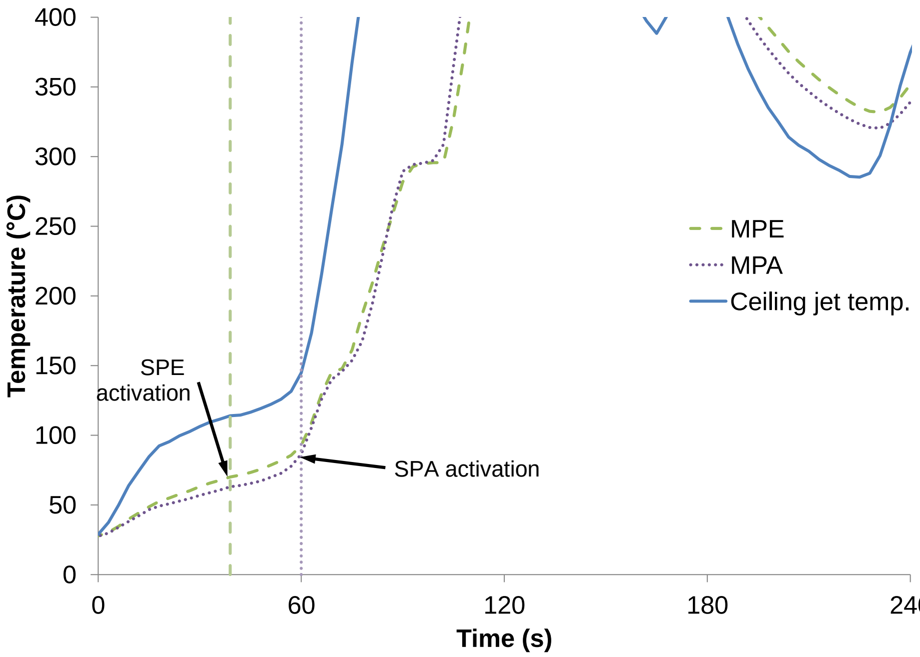


Figure B.3: Modified sprinkler temperature response, ceiling jet temperature, and standard sprinkler response time for compartment fire test A3.

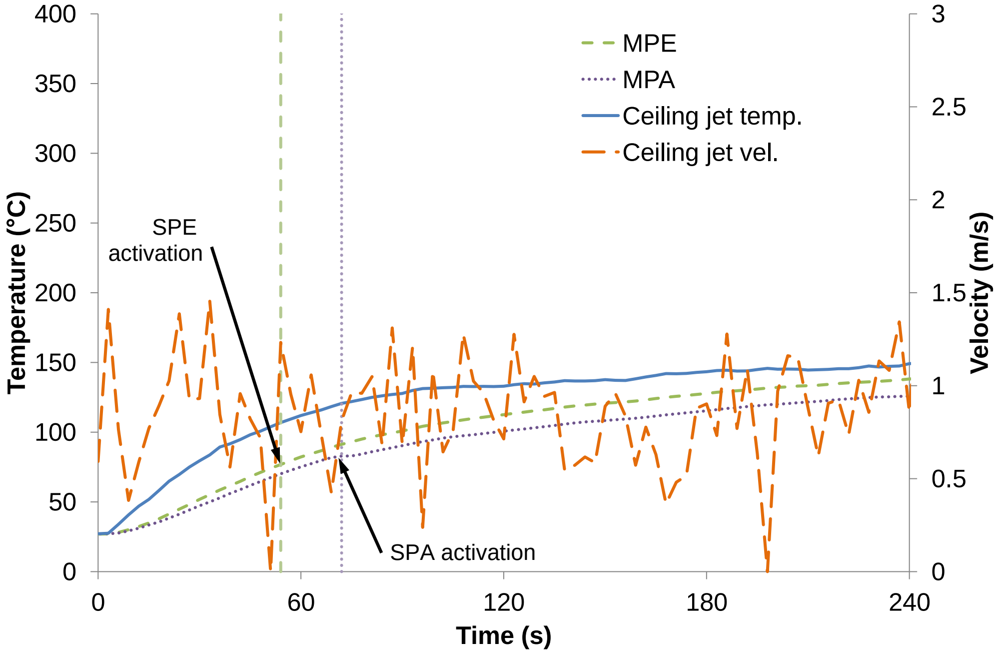


Figure B.4: Modified sprinkler temperature response, ceiling jet temperature and velocity, and standard sprinkler response time for compartment fire test B2.

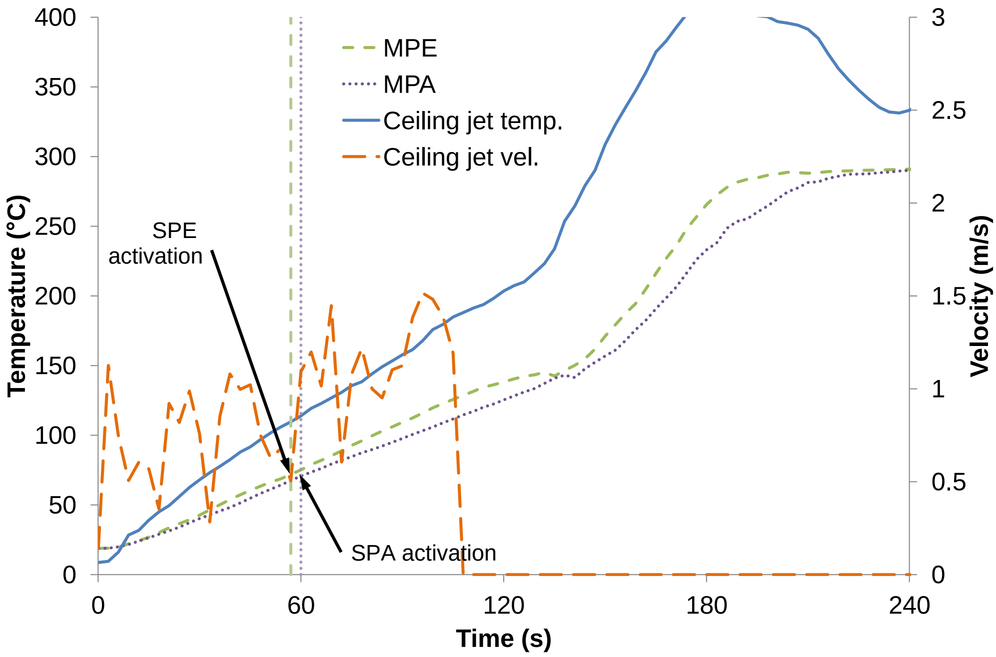


Figure B.5: Modified sprinkler temperature response, ceiling jet temperature and velocity, and standard sprinkler response time for compartment fire test C1.

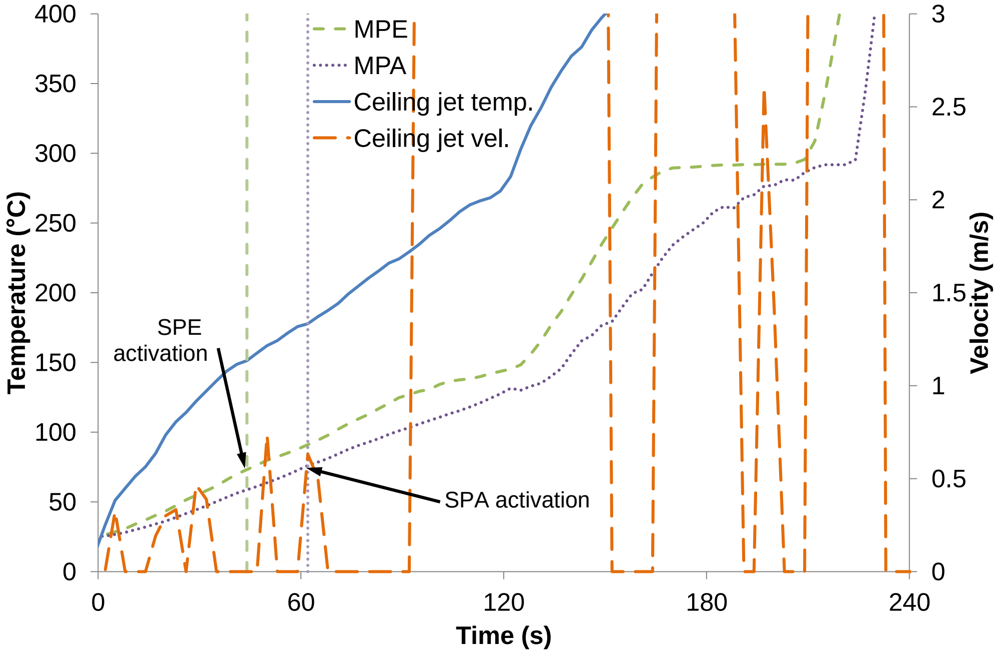


Figure B.6: Modified sprinkler temperature response, ceiling jet temperature and velocity, and standard sprinkler response time for compartment fire test D1.

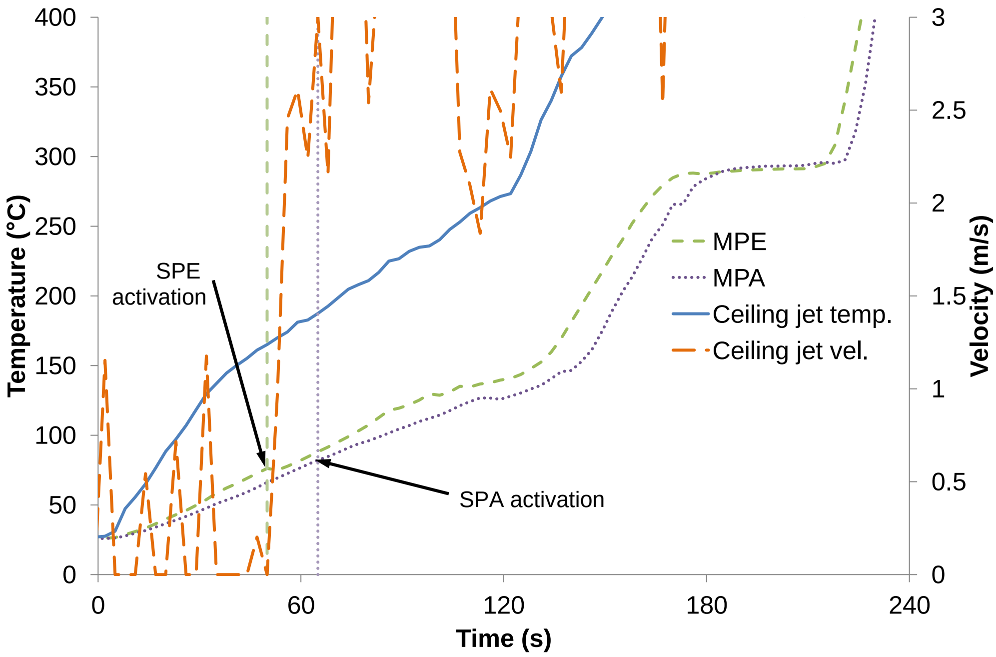


Figure B.7: Modified sprinkler temperature response, ceiling jet temperature and velocity, and standard sprinkler response time for compartment fire test D2.

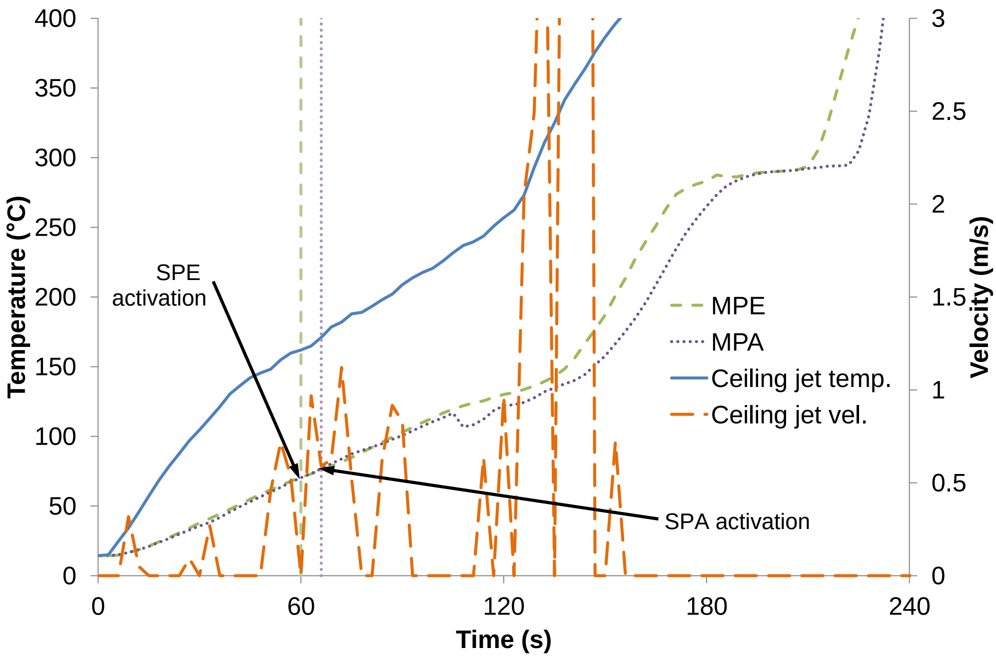


Figure B.8: Modified sprinkler temperature response, ceiling jet temperature and velocity, and standard sprinkler response time for compartment fire test D3.

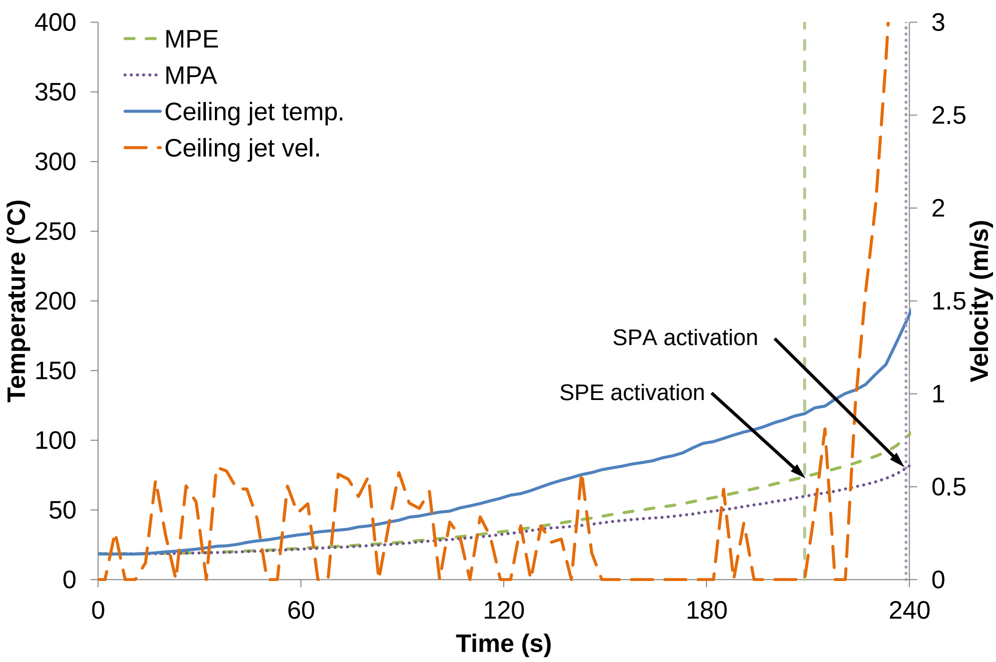


Figure B.9: Modified sprinkler temperature response, ceiling jet temperature and velocity, and standard sprinkler response time for compartment fire test E1.

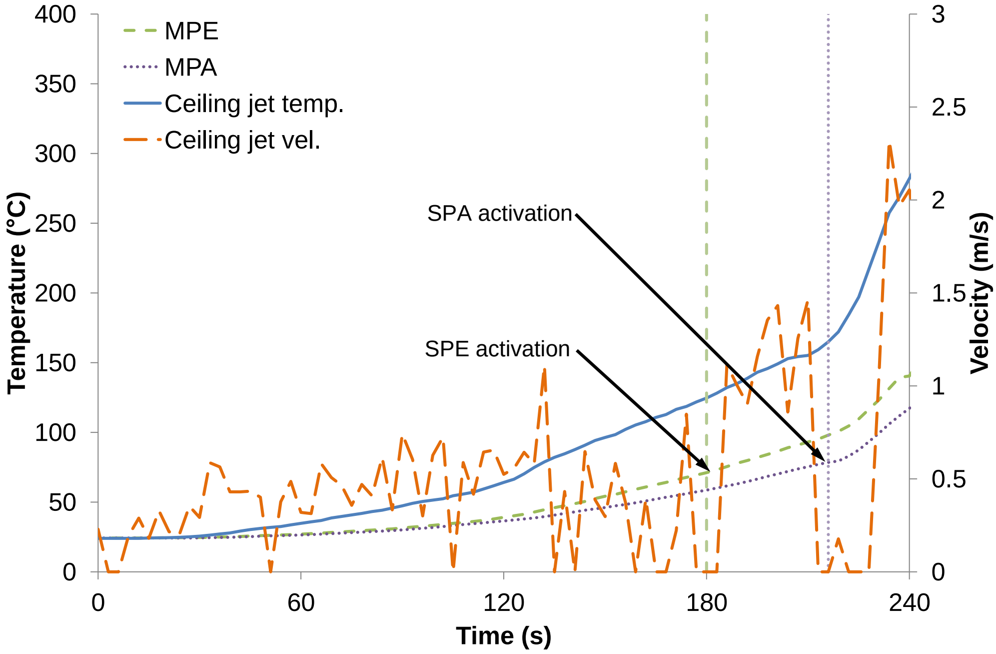


Figure B.10: Modified sprinkler temperature response, ceiling jet temperature and velocity, and standard sprinkler response time for compartment fire test E2.

APPENDIX C

ADDITIONAL FIRE DOOR RELIABILITY DATA

This appendix includes additional data collected on fire door reliability. Information on the probability that individual doors were open for each hour of the day and time recorded at each position is presented in figures organised by building.

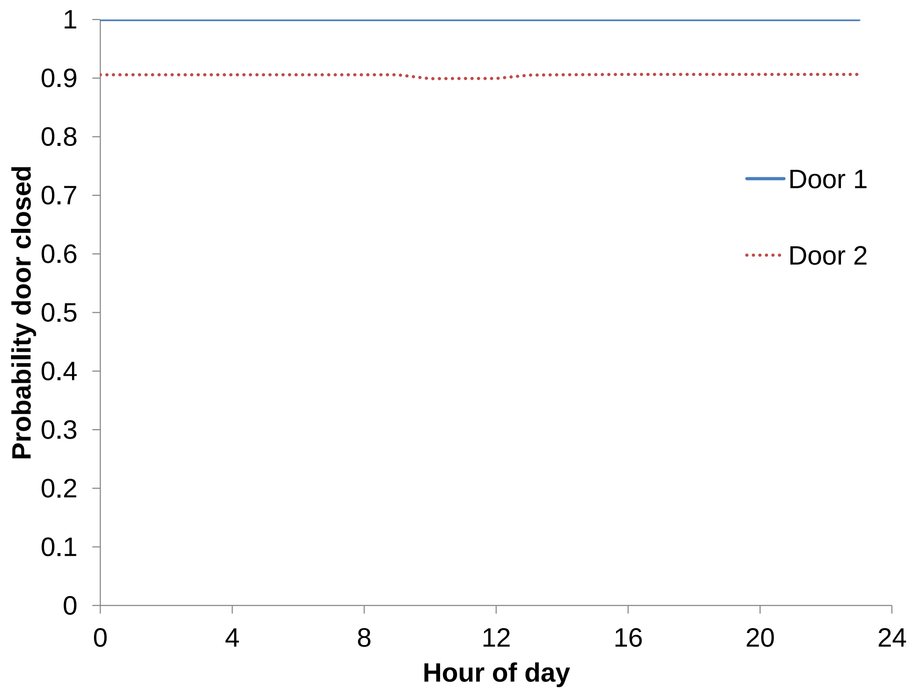


Figure C.1: Probability that tracked doors were closed by time of day for rest home no. 1.

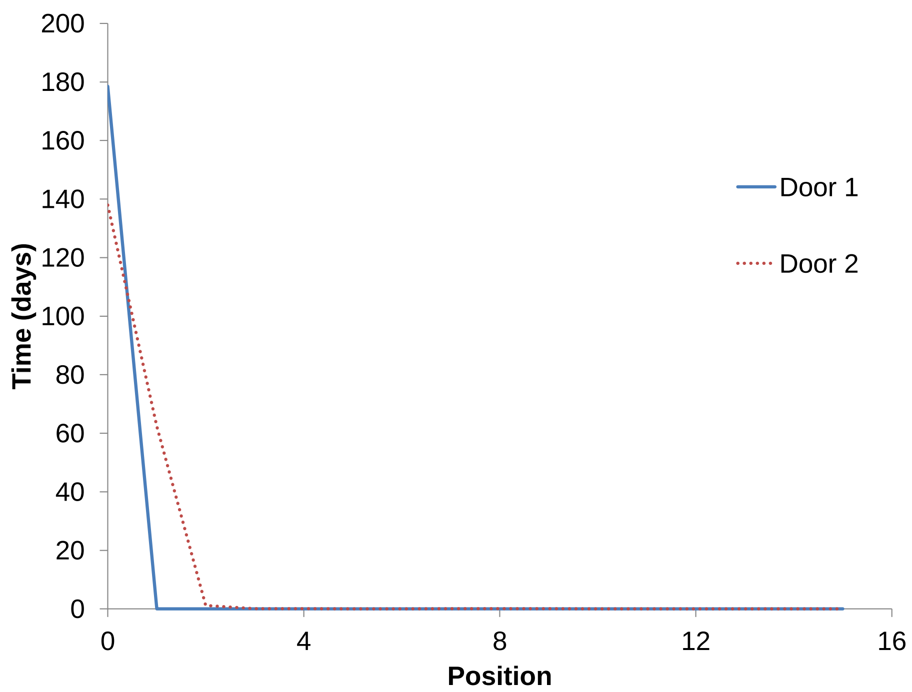


Figure C.2: Time recorded for each door position for rest home no. 1.

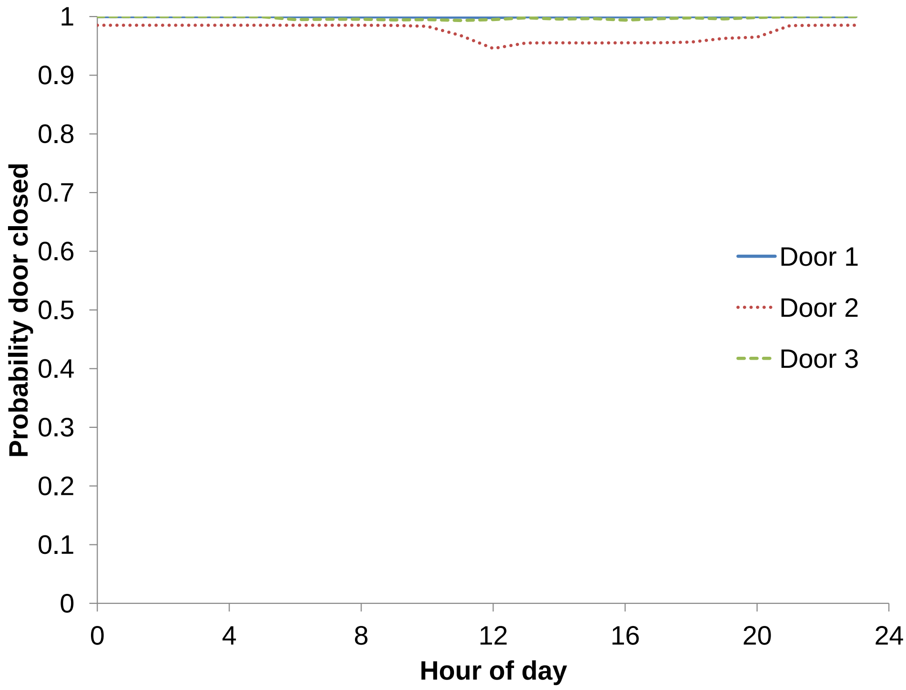


Figure C.3: Probability that tracked doors were closed by time of day for rest home no. 2.

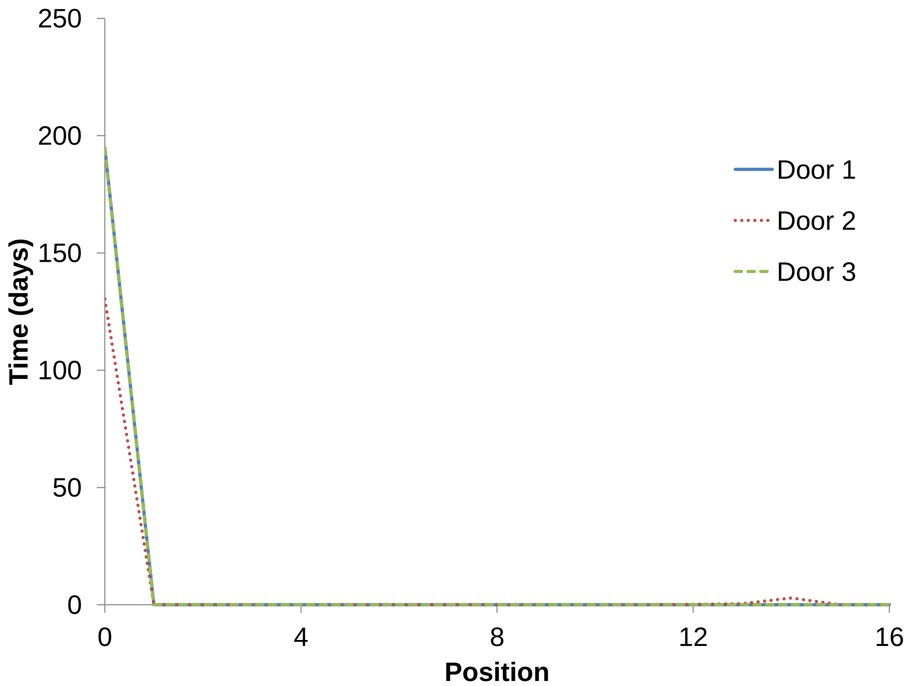


Figure C.4: Time recorded for each door position for rest home no. 2.

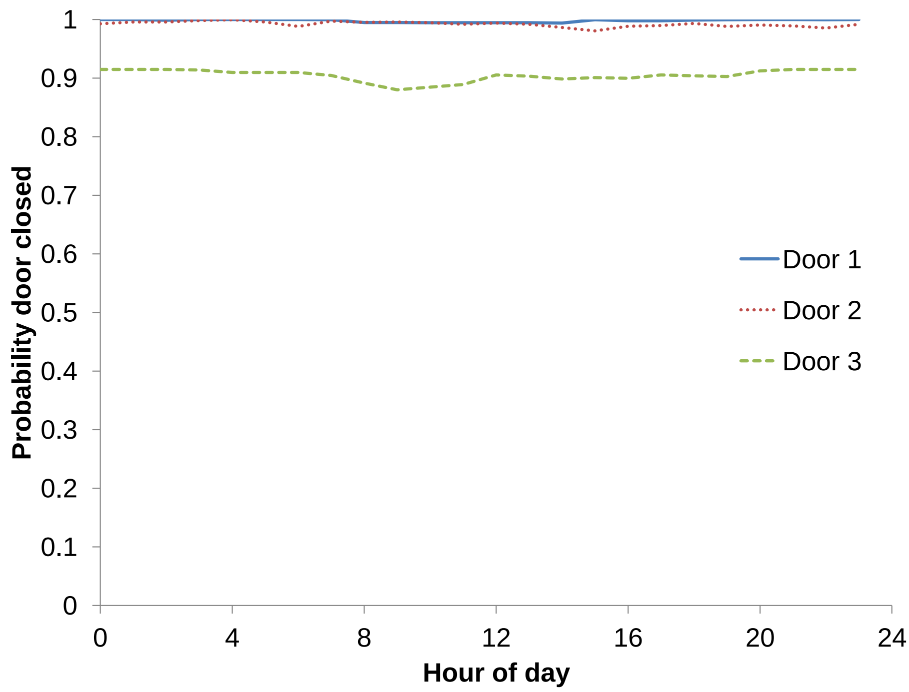


Figure C.5: Probability that tracked doors were closed by time of day for rest home no. 3.

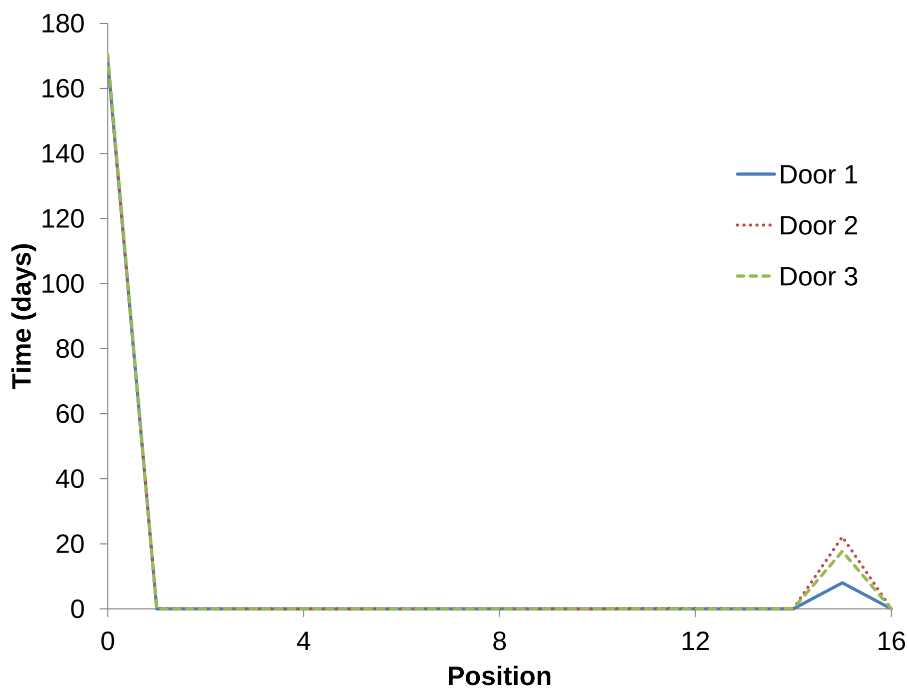


Figure C.6: Time recorded for each door position for rest home no. 3.

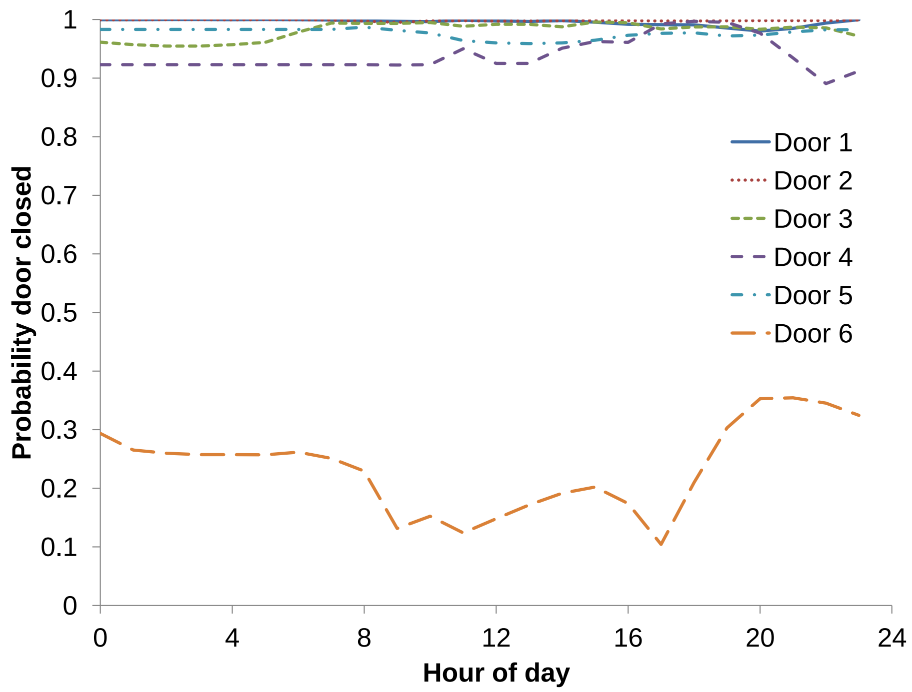


Figure C.7: Probability that tracked doors were closed by time of day for hotel no. 1.

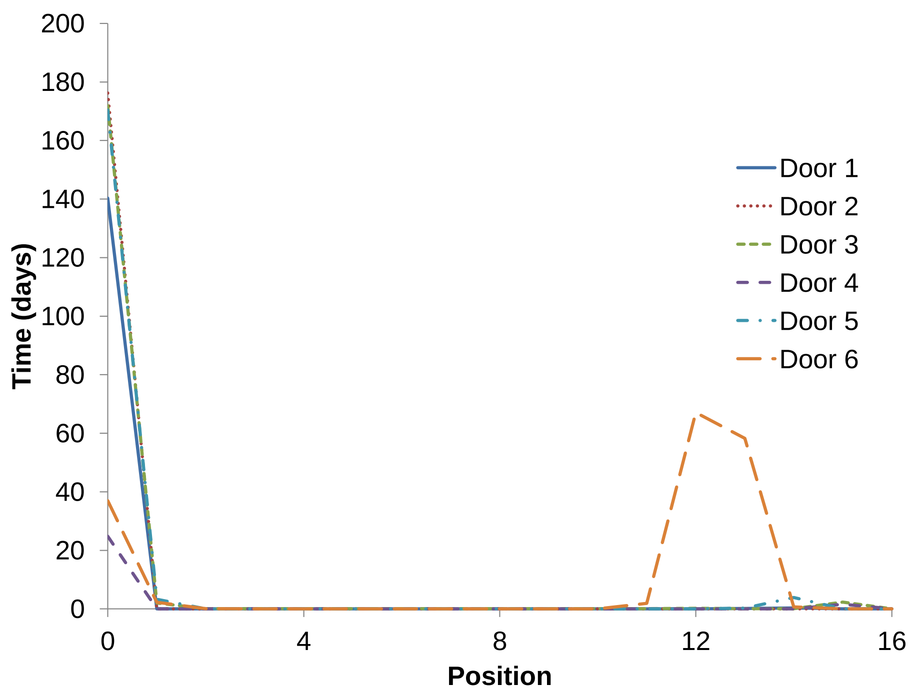


Figure C.8: Time recorded for each door position for Hotel no. 1.

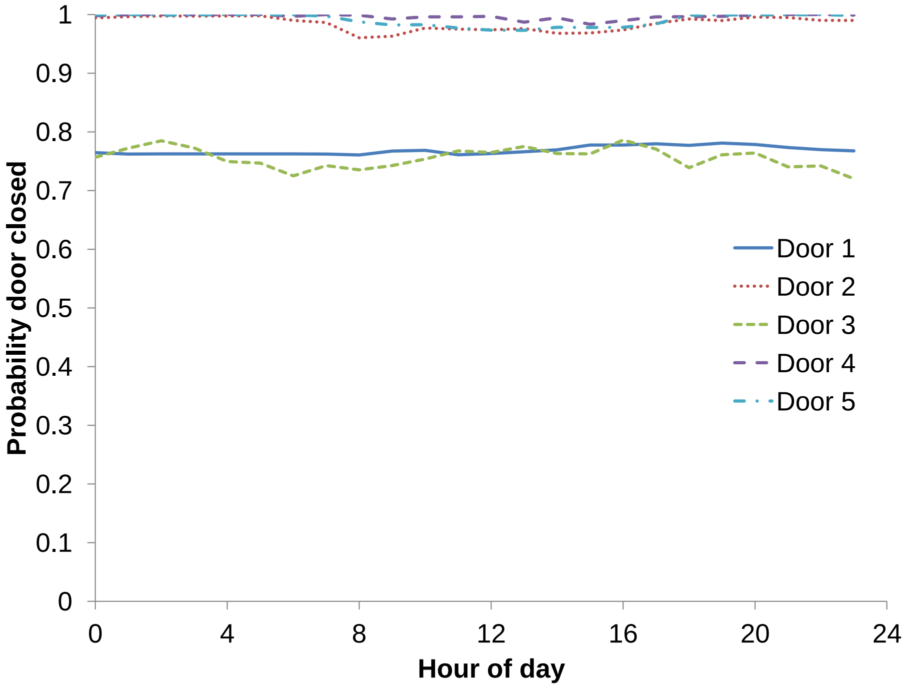


Figure C.9: Probability that tracked doors were closed by time of day for hotel no. 2.

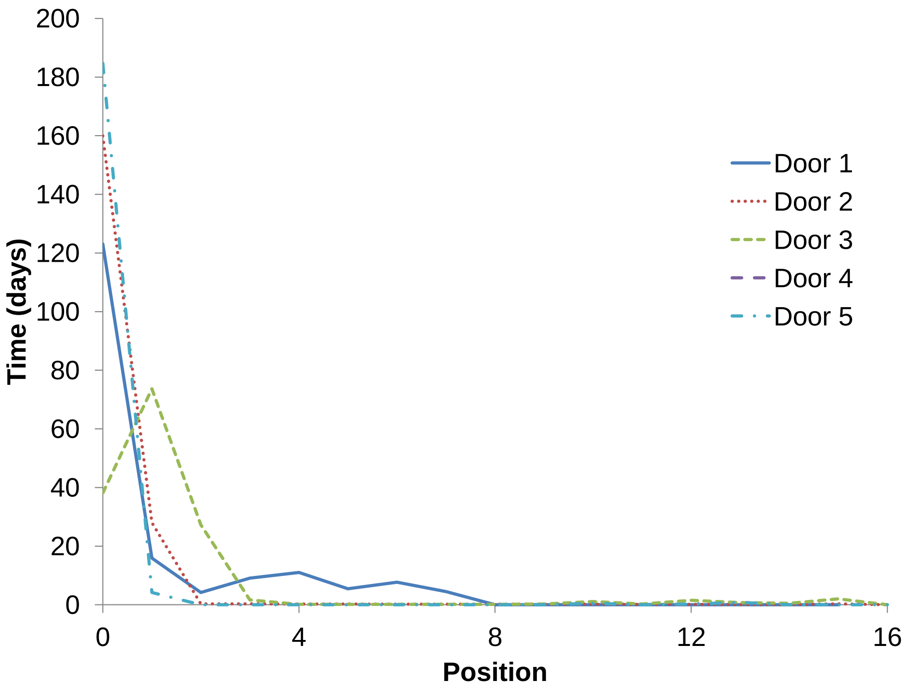


Figure C.10: Time recorded for each door position for hotel no. 2.

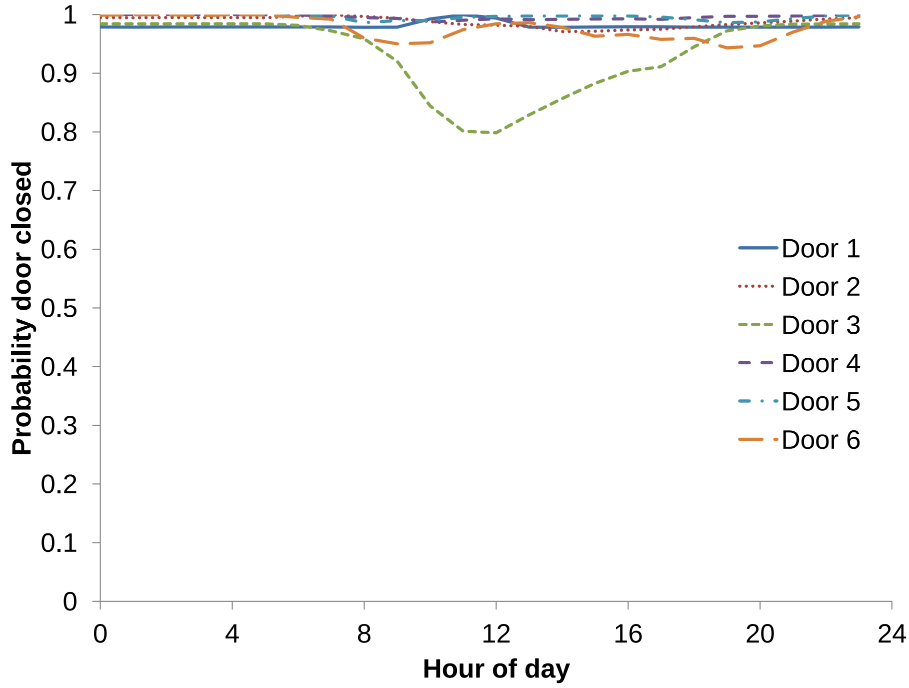


Figure C.11: Probability that tracked doors were closed by time of day for hotel no. 3.

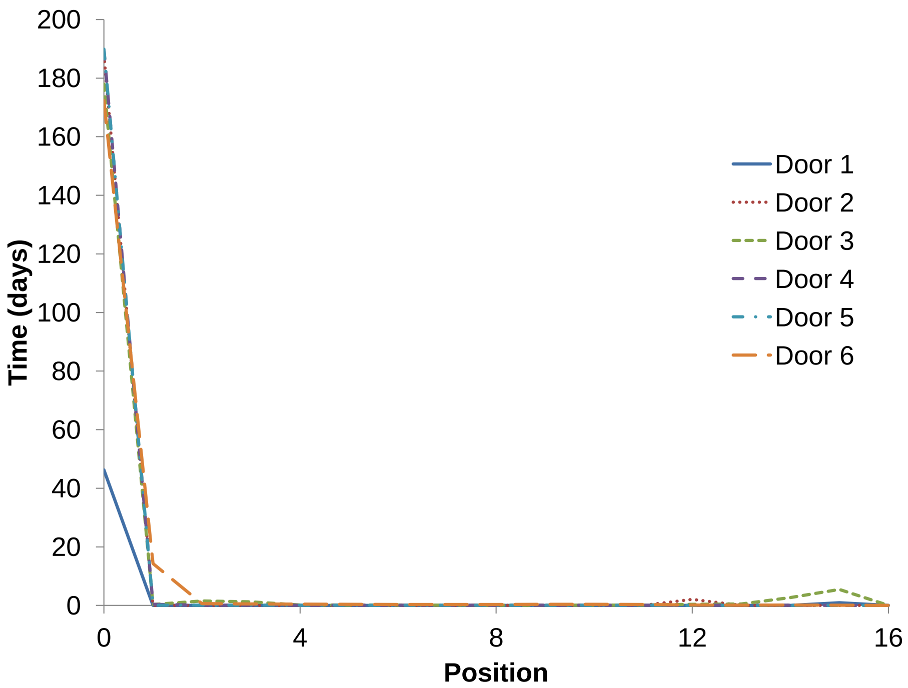


Figure C.12: Time recorded for each door position for hotel no. 3.

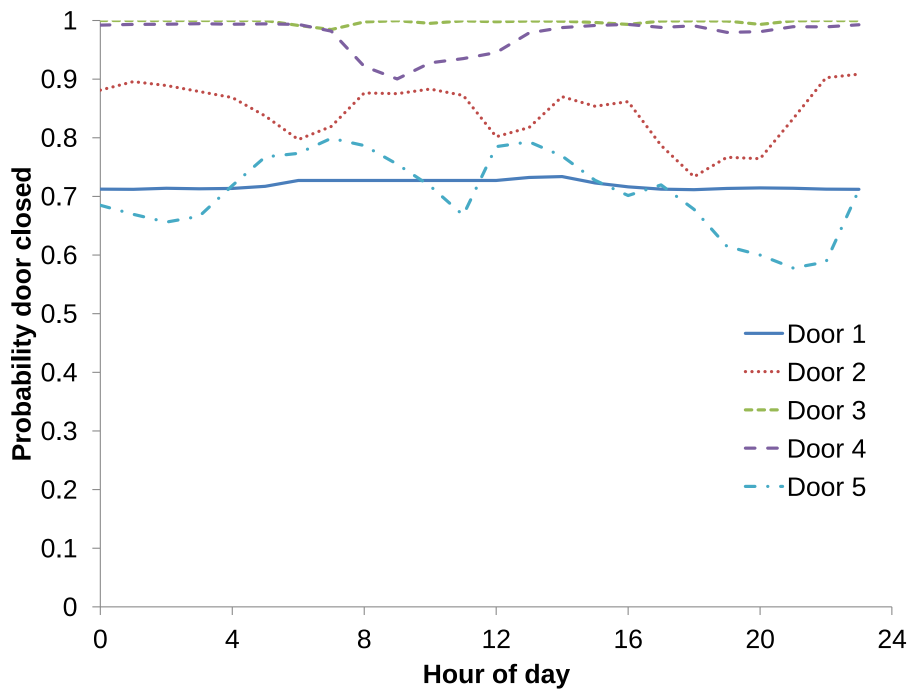


Figure C.13: Probability that tracked doors were closed by time of day for hotel no. 4, doors 1-5.

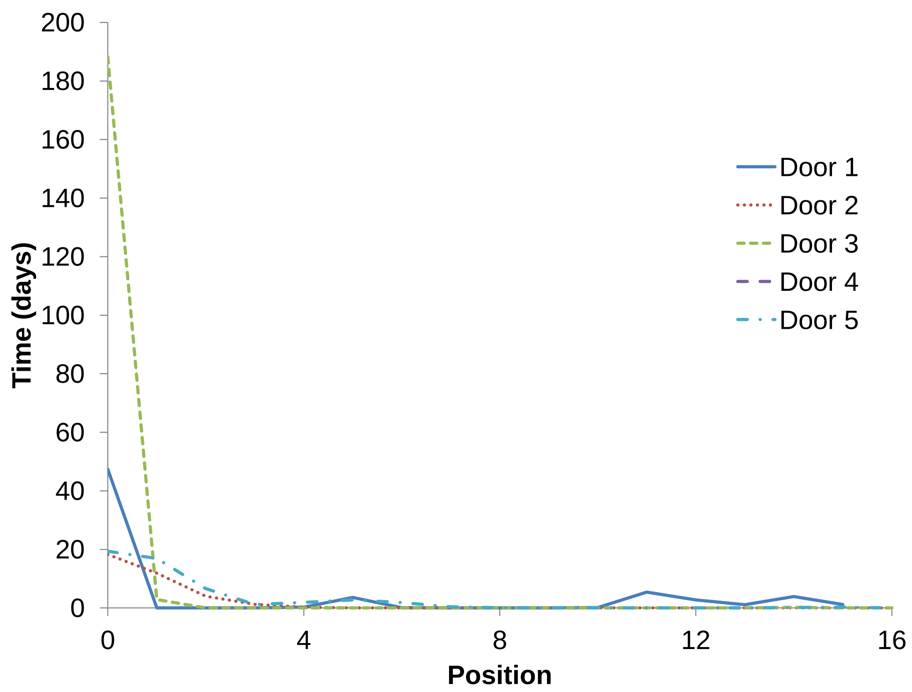


Figure C.14: Time recorded for each door position for hotel no. 4, doors 1-5.

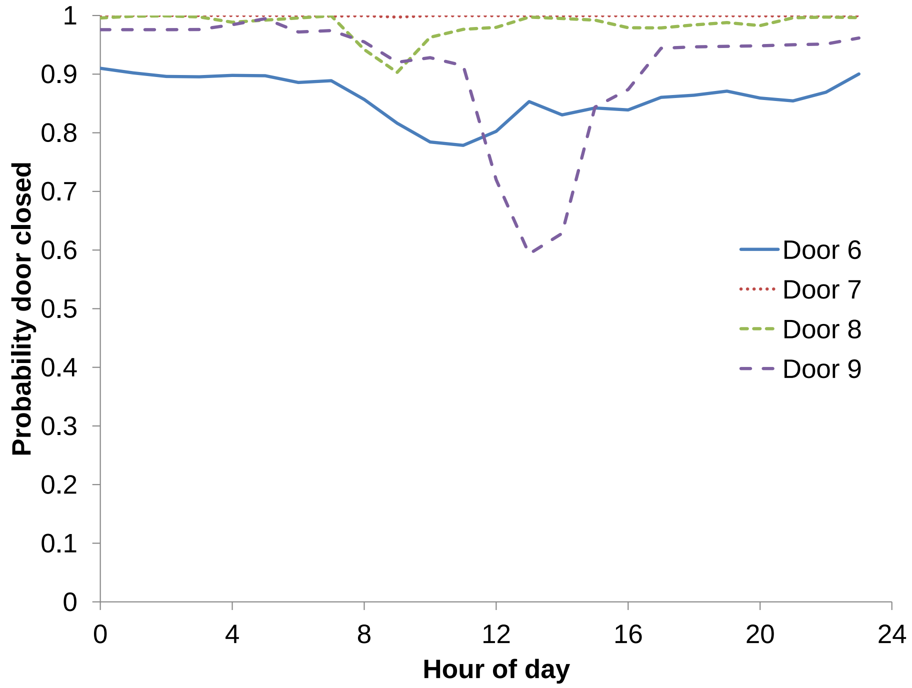


Figure C.15: Probability that tracked doors were closed by time of day for hotel no. 4, doors 6-9.

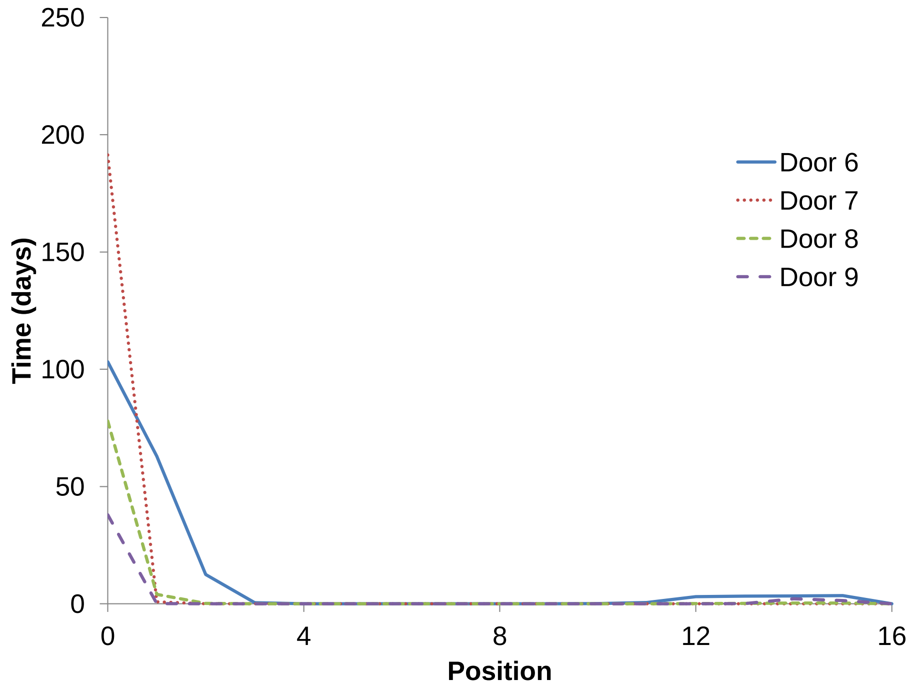


Figure C.16: Time recorded for each door position for hotel no. 4, doors 6-9.

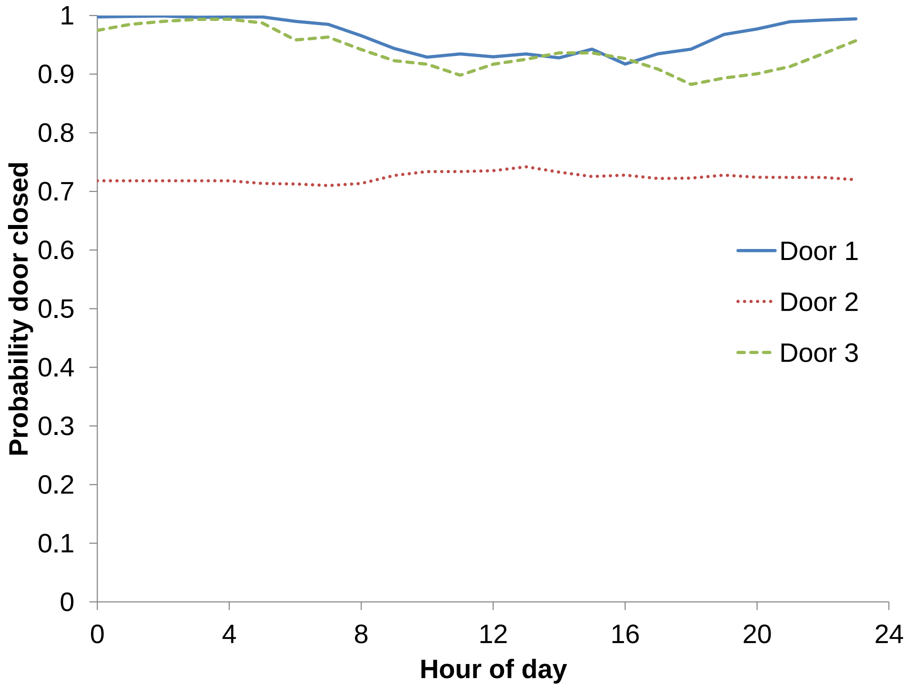


Figure C.17: Probability that tracked doors were closed by time of day for backpackers no. 1.

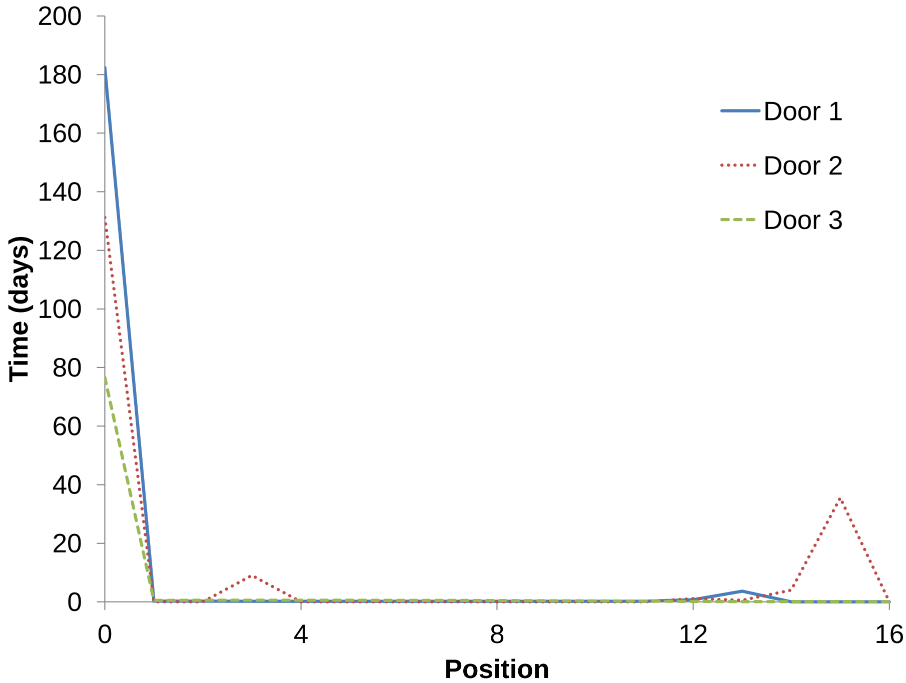


Figure C.18: Time recorded for each door position for backpackers no. 1.

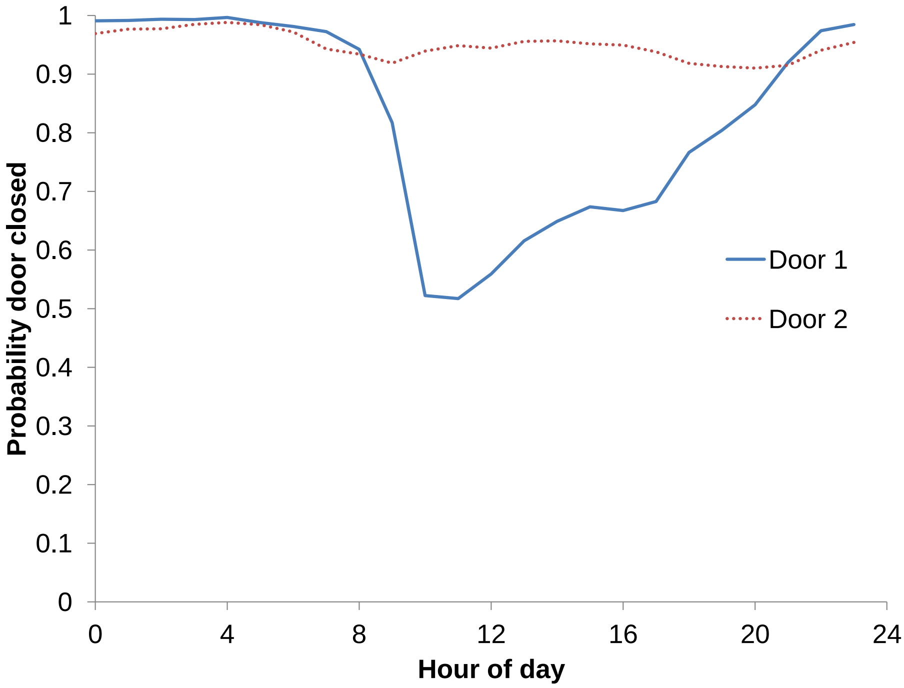


Figure C.19: Probability that tracked doors were closed by time of day for backpackers no. 2.

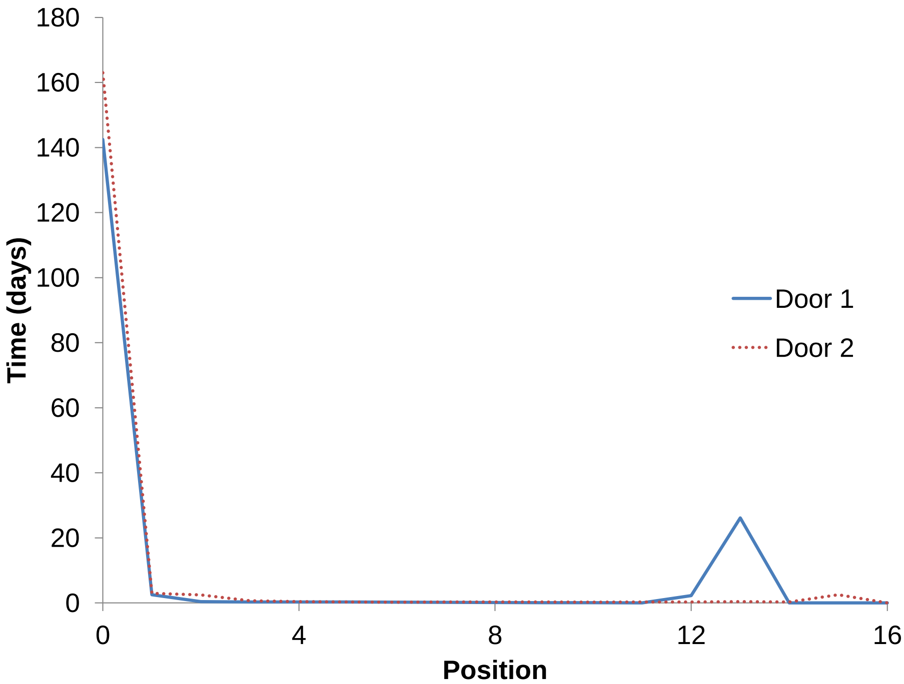


Figure C.20: Time recorded for each door position for backpackers no. 2.

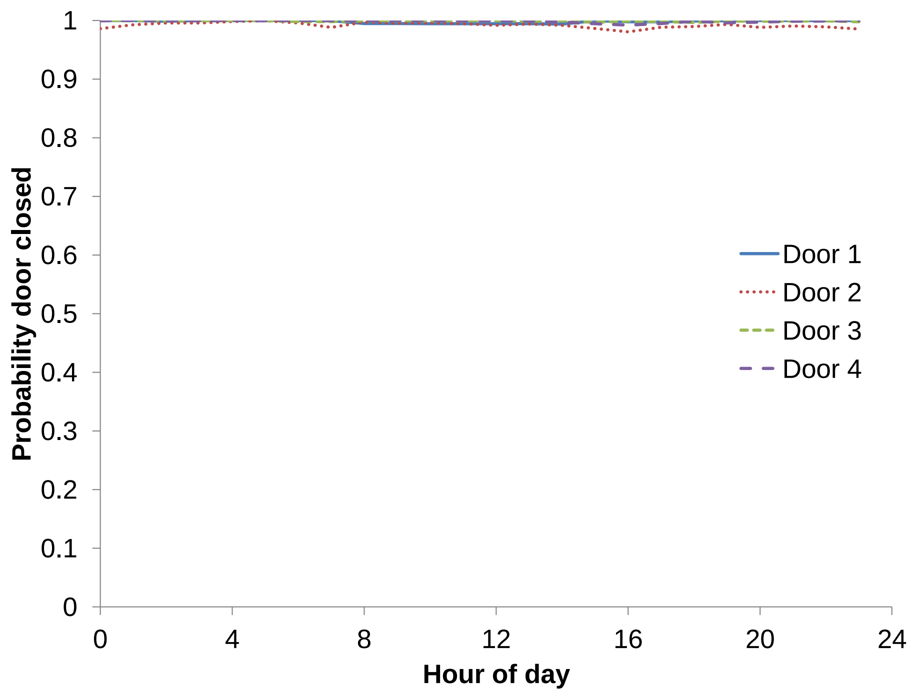


Figure C.21: Probability that tracked doors were closed by time of day for apartment/condo no. 1.

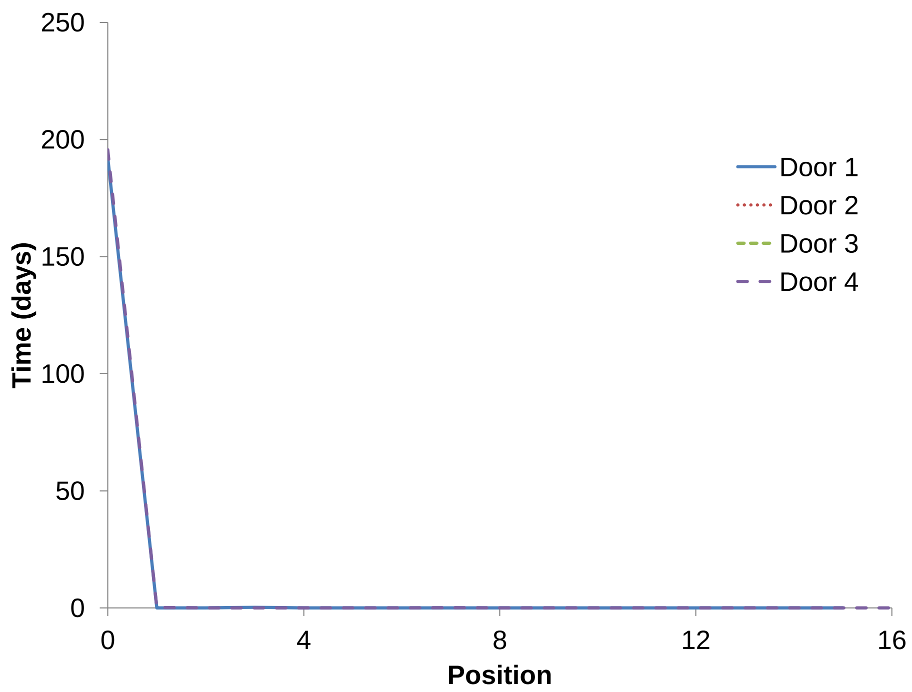


Figure C.22: Time recorded for each door position for apartment/condo no. 1.

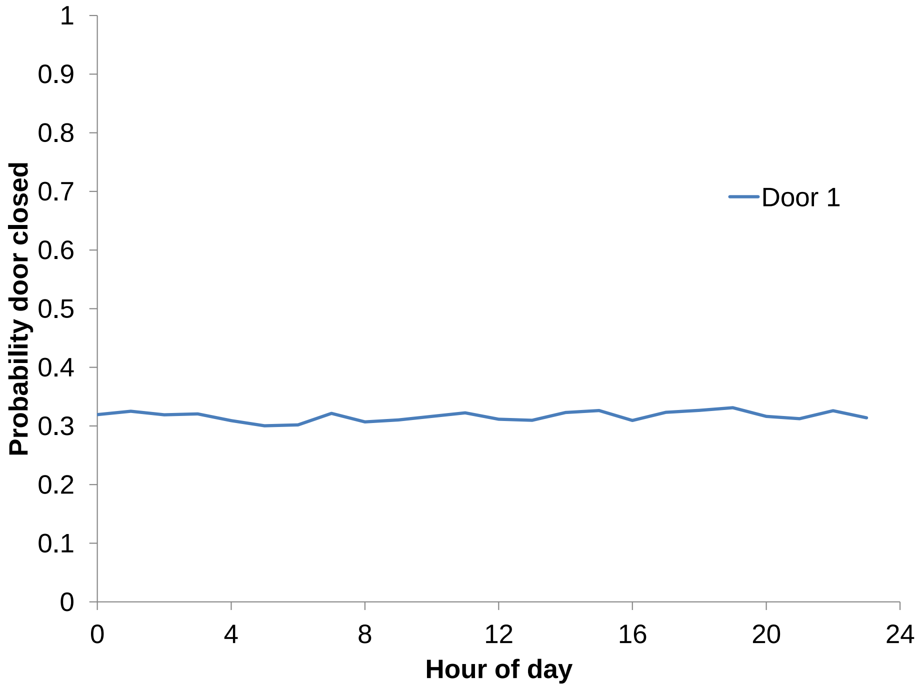


Figure C.23: Probability that tracked doors were closed by time of day for apartment/condo no. 2.

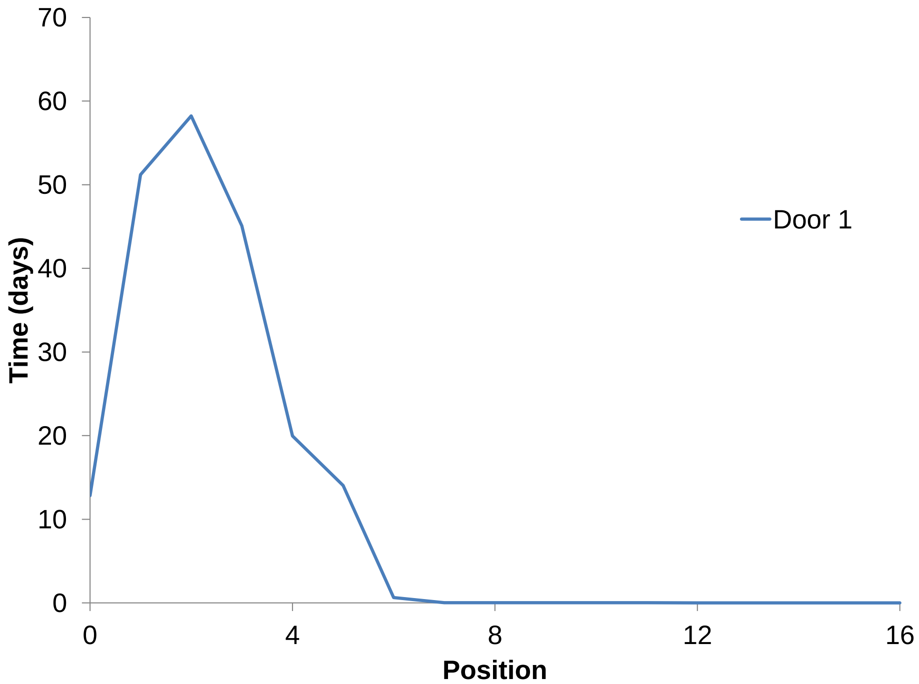


Figure C.24: Time recorded for each door position for apartment/condo no. 2.

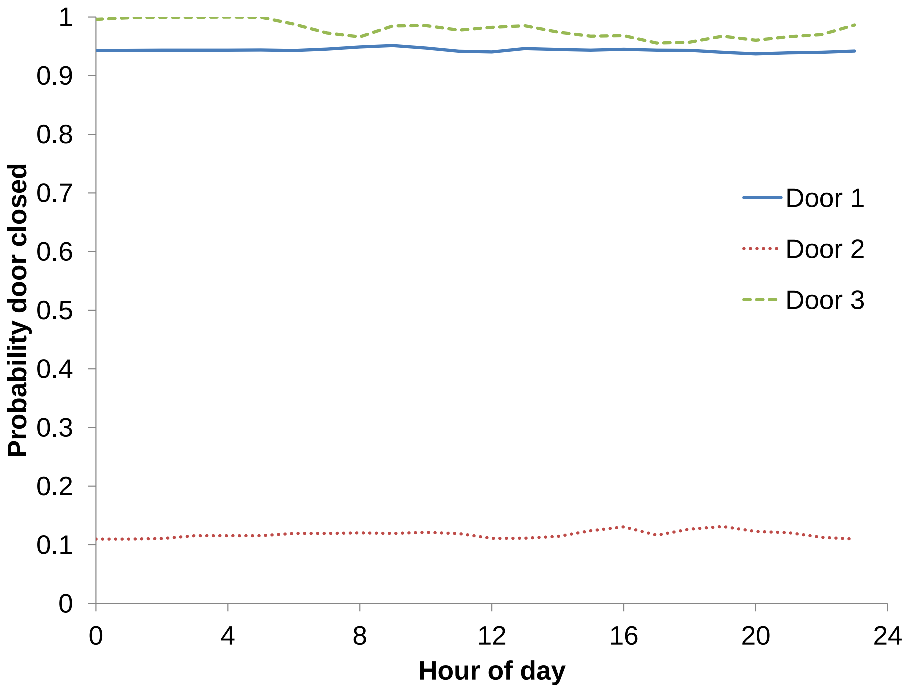


Figure C.25: Probability that tracked doors were closed by time of day for boarding house/dorm no. 1.

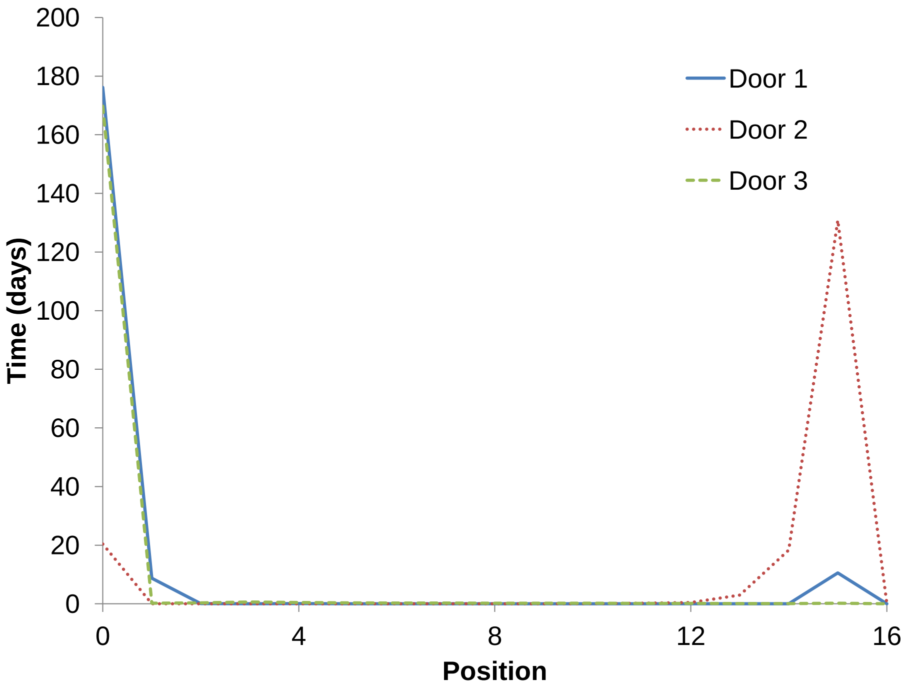


Figure C.26: Time recorded for each door position for boarding house/dorm no. 1.

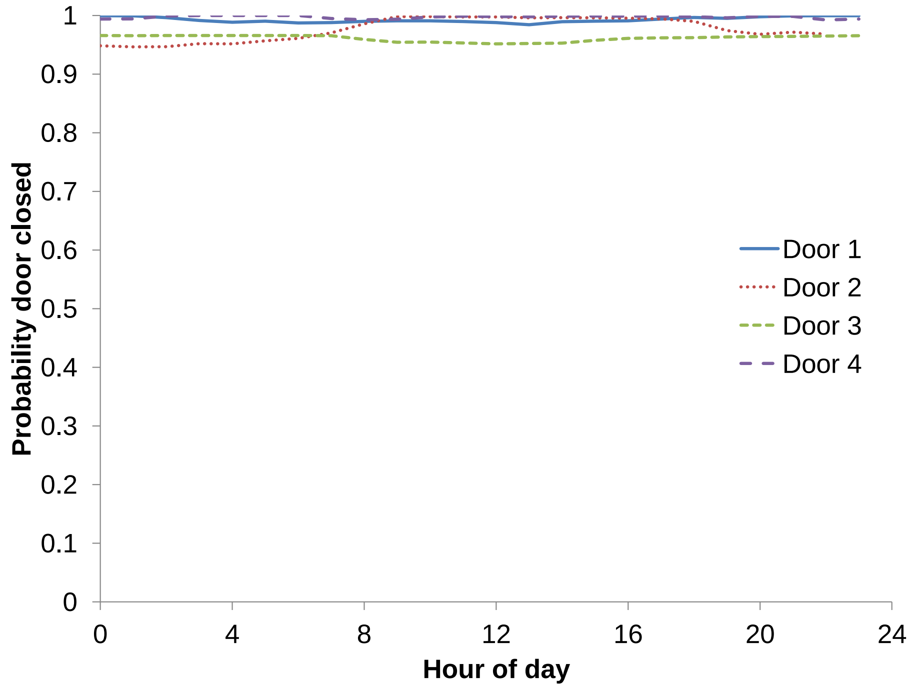


Figure C.27: Probability that tracked doors were closed by time of day for boarding house/dorm no. 2.

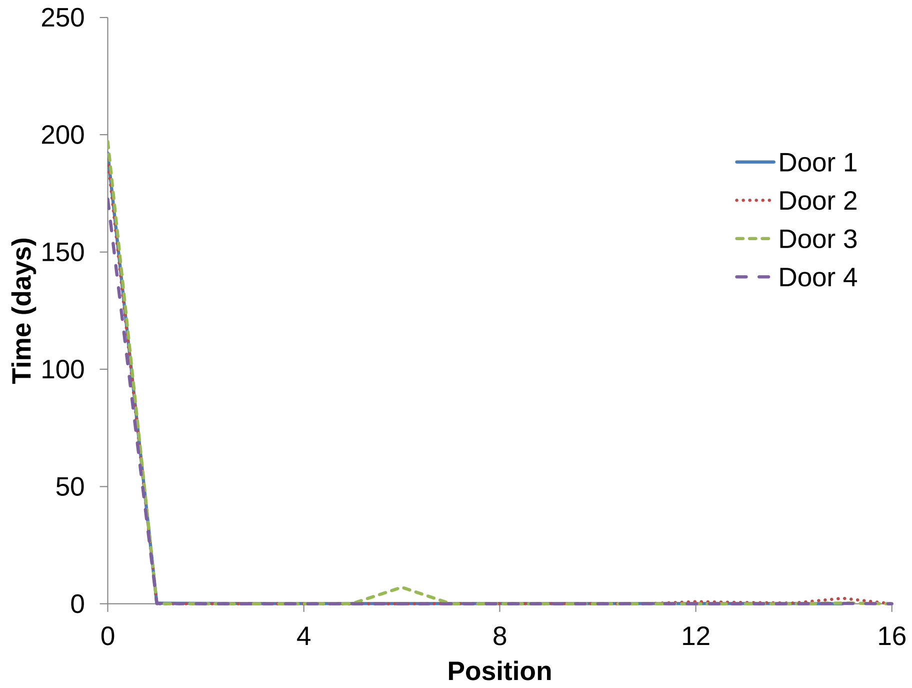


Figure C.28: Time recorded for each door position for boarding house/dorm no. 2.